Forum for Electromagnetic Research Methods and Application Technologies (FERMAT)

History of Studies on Corrugated Horns In Queen Mary College, London during 1968-70

Pradip Kumar Saha

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ABSTRACT

The second half of 1960s saw intense activities by various research groups on the development of corrugated horns (popularly known as ‘scalar horns’). This presentation aims to put on record, as a piece of history, the contributions of Pradip Kumar Saha on corrugated circular waveguides and wide-flare corrugated conical horns, while he was pursuing his doctoral research during late ’60s under the supervision of Prof. P. J. B. Clarricoats in Queen Mary College, London.

Key Words: Anisotropic boundary, Transverse corrugations, Balanced hybrid modes, Vector diffraction theory.

BIOGRAPHY

Pradip Kumar Saha obtained B.Sc.(hons) (1963), M.Tech. (1966) degrees from the University of Calcutta and Ph.D. (1970) from Leeds University, UK. During 1970 he was a P. D. Fellow at Queen Mary College, University of London. He was with the Institute of Radiophysics and Electronics, University of Calcutta since 1971 and retired as a Professor in 2008. Some of the subjects he taught are: E. M. Theory, Microwaves, Guided Wave Photonics and Optical Fiber Communication, Computational Electromagnetics. His research interests include: broadband electromagnetic transmission media, microwave circuits, antenna and plasmonics. For his pioneering contributions on Corrugated Horns, he was presented “Life Time Achievement Award” by the AP-MTT Chapter of IEEE Calcutta Section. He is a Fellow of IETE (India), Senior Member of IEEE (USA) and Fellow of West Bengal Academy of Science and Technology. After retirement from regular University service, he served as the first Director of Center for TeleInFrastruktur-India (CTIF-India), University of Calcutta, a collaborative research center established through MoA signed between University of Calcutta and Aalborg University, Denmark. At present he teaches microwaves and antenna as a visiting faculty in Swami Vivekananda Institute of Science and Technology, Maulana Abul Kalam Azad University of Technology (Formerly: West Bengal University of Technology). He is the recipient of “Eminent Teacher Award” of University of Calcutta for his dedicated service to the University and for producing scholars who have distinguished themselves.

Search for Low-Noise Feed Horns with improved performance: Situation in 1960s

Desired Characteristics:

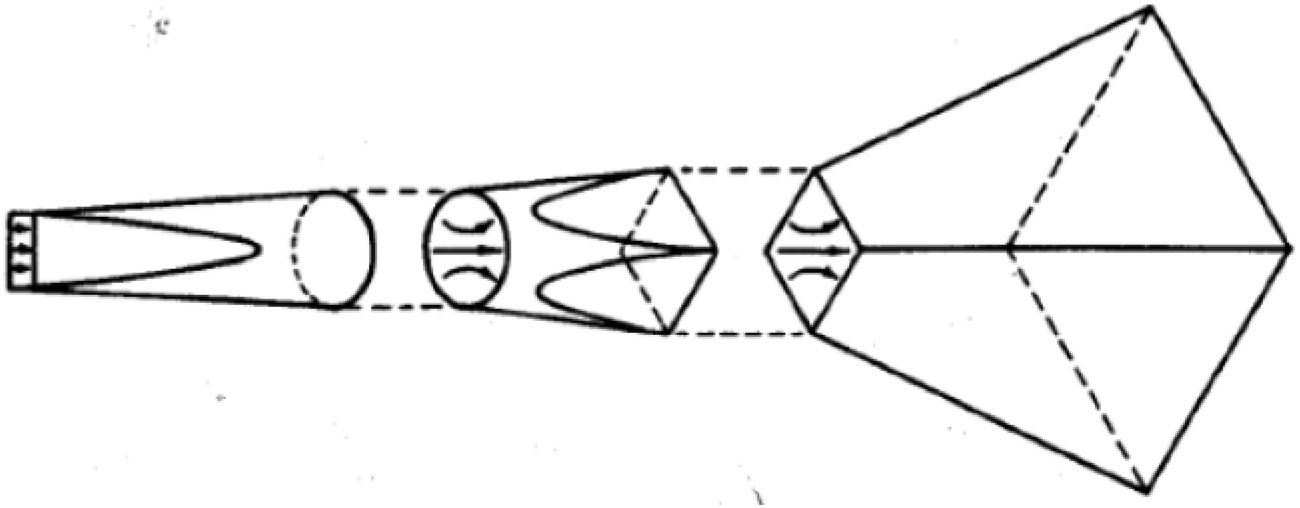
- **High Efficiency**
- **Co-polar Pattern Symmetry**
- **Low (-30 dB or better) sidelobes**

Among the various structures invented in early ‘60s, perhaps the two most notable are:

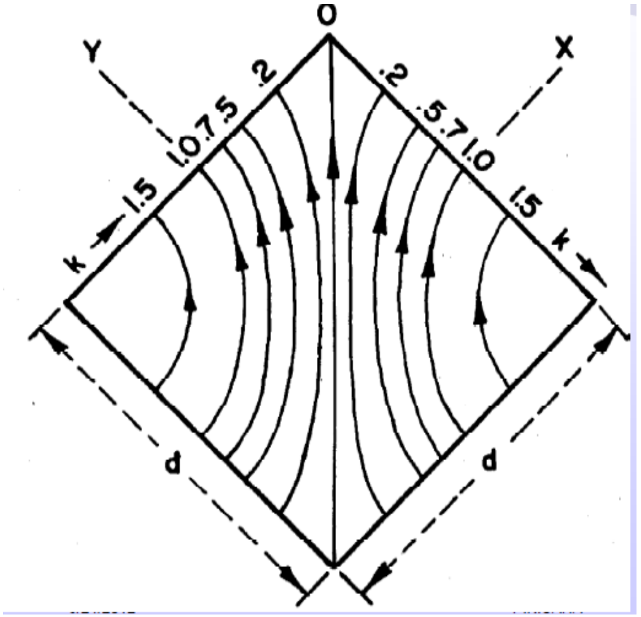
(1) Diagonal Horn (1962) – a shaped-aperture horn

(2) Potter Horn (1963) – a dual-mode conical horn.

Diagonal Horn



Rectangular waveguide to diagonally polarized horn – Mode transducer

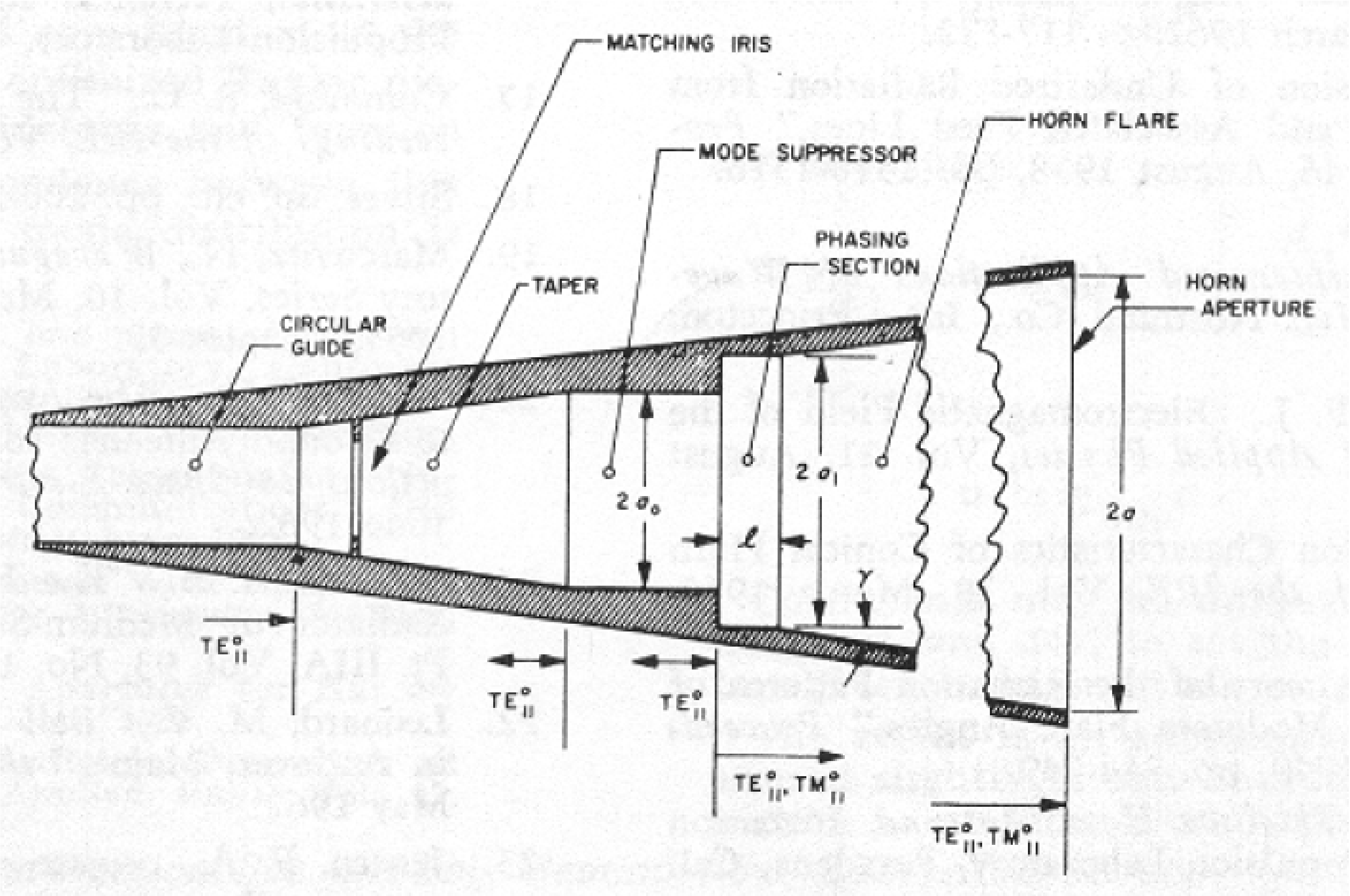

O
Y
X
.2
1.0 .7 .5
.2
.5 .7 1.0
1.5
1.5
k
k
d
d

The field pattern in the aperture

Diagonal Horn

It is a small-flare shaped-aperture (square-aperture) pure-mode horn that is diagonally polarized.

- **The co-polar pattern is almost circularly symmetric, but**
- **the peak cross-polar level is as high as -16 dB in the ± 45° planes.**
- **The sidelobes in the principal planes are about -20 dB.**


MATCHING IRIS
HORN FLARE
MODE SUPPRESSOR
PHASING SECTION
TAPER
HORN APERTURE
CIRCULAR GUIDE
2 a₁
2 a₀
ℓ
γ
2a
TE°₁₁
TE°₁₁
TE°₁₁
TE°₁₁, TM°₁₁
TE°₁₁, TM°₁₁

Dual-mode Potter Horn

Potter Horn

Potter horn is a multimode horn that uses both circular TE$_{11}$ and TM$_{11}$ modes in proper amplitude ratio to achieve:

- **aperture distribution tapered to zero in all planes,**
- **complete beam-width equalization in all planes,**
- **complete phase-centre coincidence in all planes,**
- **at least -30 dB sidelobe level in E-plane.**
- **H-plane performance remains unchanged.**

Disadvantages:

- **Narrowband**
- **Since TM$_{11}$ does not radiate axially, Potter horn has lower gain than a TE$_{11}$ horn of same aperture size.**
- **Elaborate design**

Wide-Flare TE_{11} Conical Horn: A. F. Kay (1962)

Kay initiated a new approach to feed design. He proposed and investigated wide-flare TE_{11} conical horns as low-noise feed.

- **Such horns are characterized by Δ (the maximum phase deviation of spherical phase front from aperture plane) > $\lambda/2$, unlike "diffraction limited" horns with $\Delta<\lambda/2$.**
- **Phase centres are at the throat of the horn.**
- **Patterns have virtually no sidelobes.**
- **Beamwidth, to first approximation, is independent of λ.**
- **At $\theta=\theta_0$ (Half Flare Angle), E-plane pattern level is 6-9 dB depending on θ_0 and independent of λ; in H-plane it is 13-25 dB depending on θ_0 and slightly on Flare Length/λ ratio.**
- **Heavy E-plane edge illumination spoils phase-centre coincidence and lowers secondary aperture efficiency.**

Wide-Flare Corrugated Conical Horn: A. F. Kay (1964)

- **Kay found that if the inner wall of wide-flare conical horn was corrugated with transverse grooves that present capacitive series reactance to the incident field in the E-plane, radiation patterns are almost symmetrical over a broad frequency band.**
- **Kay reported the measured radiation pattern of such a horn of 70^o half flare angle.**
- **The pattern symmetry indicated that the boundary conditions for the radially flowing field are the same in every axial plane independent of polarization.**
- **This boundary condition was explained from an analogy with plane corrugated surface.**

- **If a plane wave, traveling transverse to the grooves on a plane corrugated surface, is incident at an angle ψ to the perpendicular to the surface, the reflection coefficients for TE/TM waves are given by**

$$\boldsymbol{R_{TE} = -1}$$

$$\boldsymbol{R_{TM} = \frac{\cos\psi + jX}{\cos\psi - jX}}$$

where *X* is the surface reactance.

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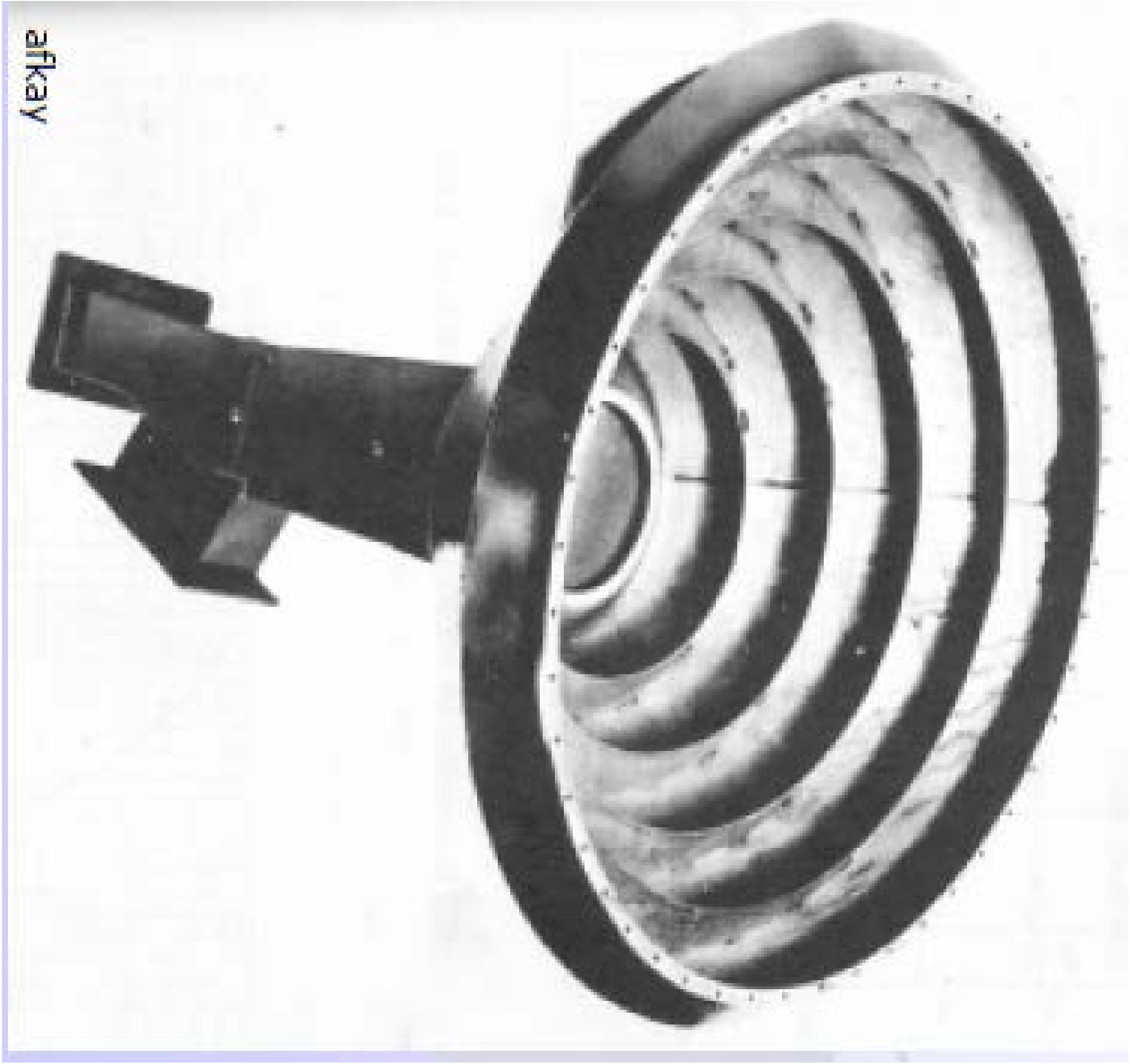
- **In the limit $\psi \rightarrow 90^{o}$, $R_{TE} = R_{TM} \rightarrow -1$. Implication: on the corrugated surface, tangential components of both E and H vanish.**
- **This can be true for both inductive (X>0) and capacitive(X<0) surfaces.**
- **Inductive surface is inappropriate for antenna applications as it supports surface waves which do not vanish on the surface. Only capacitive surface is desirable.**
- **Thus, a boundary condition which is independent of polarization, produces a field that is independent of polarization. Accordingly, such a feed was named – Scalar Feed.**

Scalar Feed
Half Flare Angle - 70º

A.F. Kay (1964)



Hybrid Mode Waveguide Feed:
Minnett and Thomas (1966)

- **Study of the focal field of a circularly symmetric parabolic reflector, illuminated by a linearly polarized plane wave, together with the concept of symmetric radiation field led to the development of hybrid mode waveguide feeds.**

- **The scattered field at the focal plane of the reflector is a superposition of axially propagating hybrid waves that were identified with the fast hybrid modes of unit azimuthal dependence in a transversely corrugated circular waveguide.**

- **It was shown that a waveguide to support the focal-field hybrid waves, its boundary must satisfy $X_z.X_\xi = - \eta_0^2$, where X_z is longitudinal surface reactance and X_ξ is circumferential surface reactance, η_0 is free-space wave impedance.**

- **Transversely corrugated surface with appropriate groove depth and sufficient number of corrugations per wavelength, approximately satisfies this condition with $X_z= \infty$ and $X_\xi= 0$.**

- **The condition can also be satisfied by longitudinally grooved surface with $X_z= 0$ and $X_\xi= \infty$. However, with such boundary, the waveguide would support pure TM_{1n} modes and hence would be unsuitable.**

In this backdrop, Pradip Kumar Saha embarked on doctoral research under the supervision and guidance of Professor P. J. B. Clarricoats in Queen Mary college, University of London, in 1968.

Aim: Study of Propagation and Radiation Characteristics of Corrugated Waveguides and Corrugated Horns.

The approach was straightforward theoretical analysis and experimental verification of theoretical results wherever feasible.

This presentation highlights the notable results of the investigations.

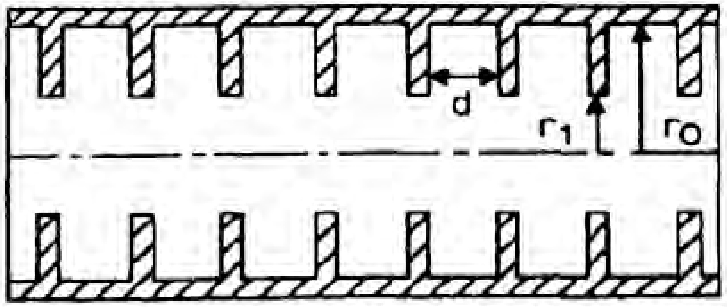
First Phase: Study of Modal Properties of Circular Waveguide with Transverse Corrugations to Create Anisotropic Boundary

Aspects Explored:

- **Characteristic Equation**
- **Circularly Symmetric Modes**
- **Spectrum of Azimuthally Dependent Hybrid Modes**
- **Dispersion Diagrams**
- **Balanced Hybrid Condition**

Lowest Hybrid Mode HE_{11} Characteristics:

- **Field Pattern**
- **Power Flow**
- **Attenuation**



Slot Depth $g=r_0-r_1$,
Slot Width= d

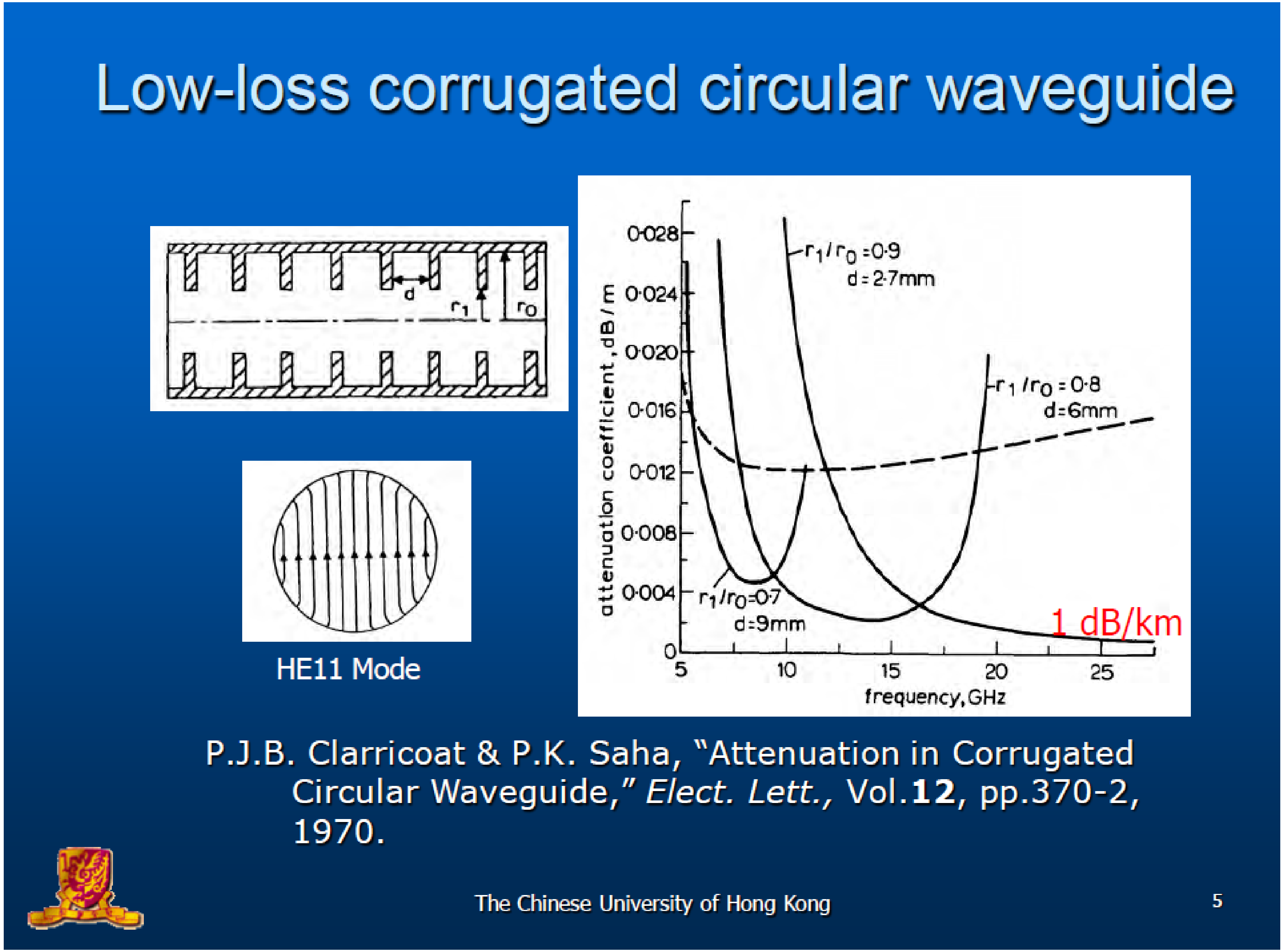
Balanced Hybrid Condition

- **In theory, perfect pattern symmetry and zero cross-polarization occur at the design frequency under "Balanced Hybrid" condition (BHC), when the corrugation depth is about one quarter of the wavelength.**
- **For large apertures (large waveguide radii), slot depth *g* (for BHC) $\approx \lambda/4$. For small apertures, $g > 0.25\lambda$, being $\approx 0.3\lambda$ for 2λ aperture.**
- **Example: For a 10 GHz waveguide with aperture diameter of 3λ, slot depth of 0.3λ, peak cross-polar level of aperture field in 45^o plane is –47 dB.**

Attenuation in Corrugated Circular Waveguide

An interesting result emerged from the study of modal properties. It was found that the theoretical attenuation of HE_{11} mode under balanced hybrid condition and over a band around the frequency corresponding to BHC can be lower than the attenuation in a TE_{11} circular waveguide of same inner diameter. One needs to be careful in comparing the attenuation as the low-frequency cut-off of the two guides are different. Also, to realize this low-loss feature, the number of grooves per wavelength should be the minimum necessary to produce the continuous anisotropic boundary.

We reproduce a slide from K. C. Kao's Nobel Lecture where he reports this result on low-loss feature of Corrugated Circular Waveguide under balanced hybrid condition.



Low-loss corrugated circular waveguide

d
r_1
r_0
attenuation coefficient, dB/m
0·028
0·024
0·020
0·016
0·012
0·008
0·004
0
5
10
15
20
25
frequency, GHz
r_1/r_0 = 0·9
d = 2·7mm
r_1/r_0 = 0·8
d = 6mm
r_1/r_0 = 0·7
d = 9mm
1 dB/km

HE11 Mode

P.J.B. Clarricoat & P.K. Saha, "Attenuation in Corrugated Circular Waveguide," *Elect. Lett.*, Vol.**12**, pp.370-2, 1970.

λ/d ≈ 5 at BHC ; ≈ 3 at 1.5 * BHC

Second Phase: Radiation From Corrugated Circular Waveguide

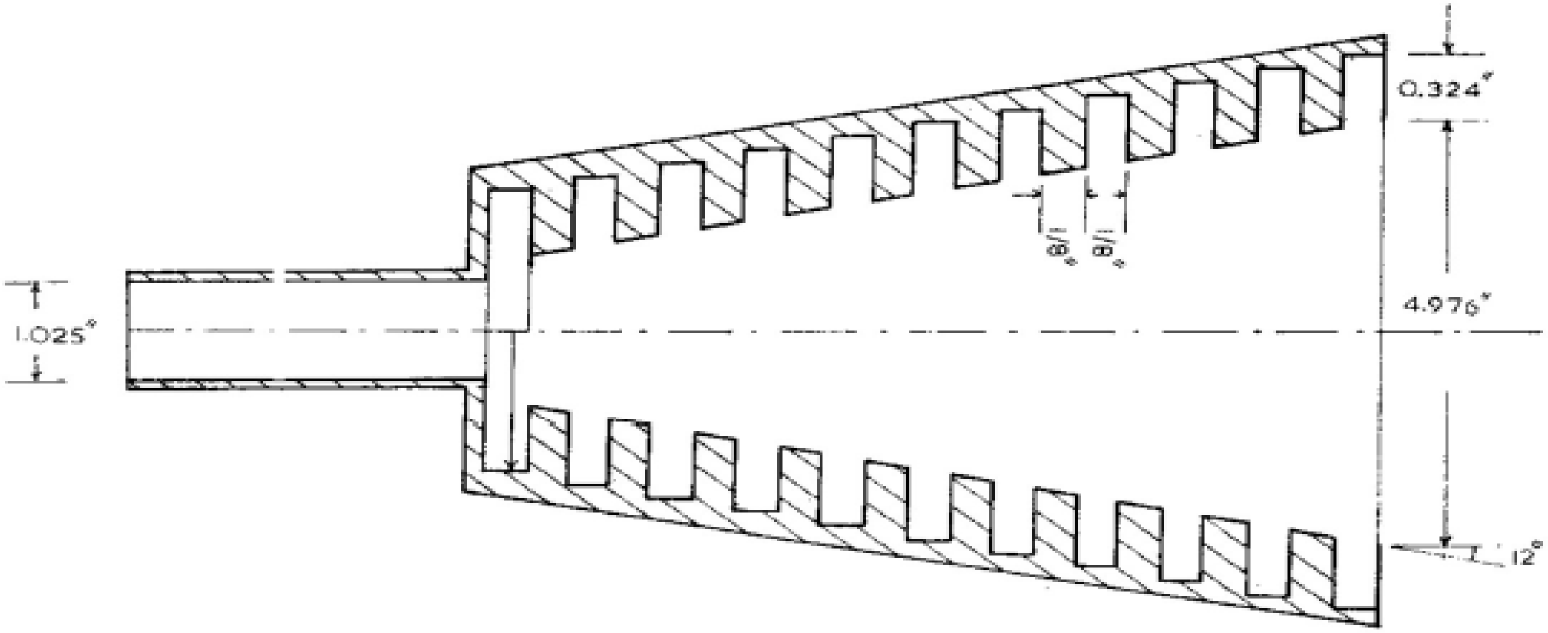
Aspects Explored:

- **Derivation of Far-field Pattern by Kirchhoff-Huygen Integration**
- **Hybrid and TM_{0n} Mode Radiation Patterns**
- **Detailed Study of HE_{11} Mode Radiation Patterns**
- **Performance of Parabolic Reflector with Corrugated Waveguide Feed**
- **An Experimental Narrow-Flare Corrugated Horn of 12^o Half Flare Angle Fabricated and Tested**
- **Patterns and Input VSWR Measured over 8.5 – 11.0 GHz**

Highlights of Second Phase Results:

- **The co-polar pattern of HE_{11} mode at BHC is circularly symmetric and the sidelobe level is about -30 dB.**
- **At 1.5 times BHC, the diffraction-limited beamwidth decreases but both the loss in pattern symmetry and increase in sidelobe level are marginal.**
- **A narrow-flare (half-flare of 12^o) corrugated horn (corrugations perpendicular to the waveguide axis) was fabricated and tested successfully.**
- **The theoretical pattern of the experimental horn was computed incorporating the quadratic phase error at the aperture.**
- **The agreement between theoretical and measured patterns over 8.5 - 11.0 GHz (BHC at 9.0 GHz) was excellent.**
- **The maximum value of measured input VSWR over this band was about 1.3, indicating very good match at the junction of circular waveguide and corrugated horn.**

Narrow Flare Corrugated Conical Horn


0.324"
1/8"
1/8"
4.976"
1.025"
12°

Experimental X-Band 12^o Half Flare Corrugated Horn

Theoretical and Measured Patterns of Experimental 12° Half Flare Horn
8.5 – 11.0 GHz

Computed Pattern:

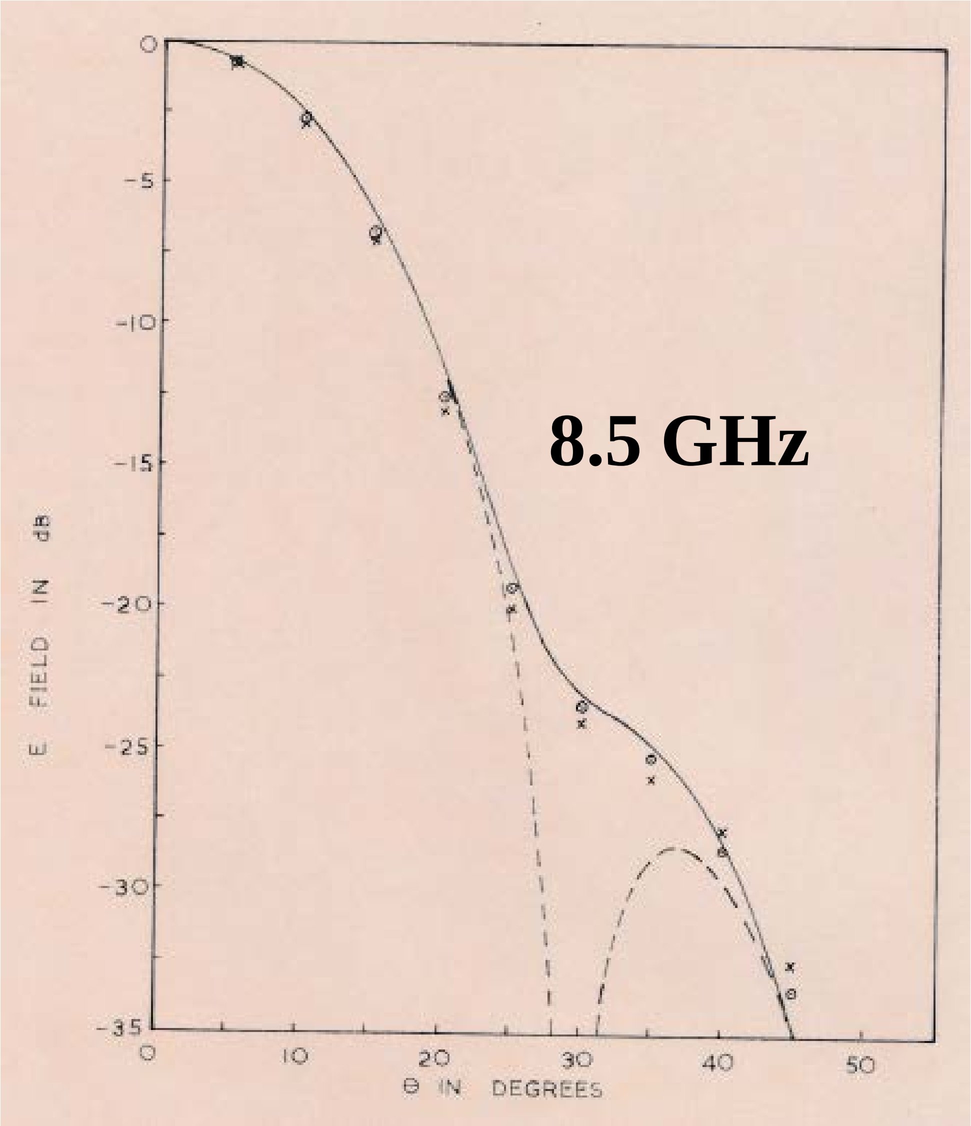
(- - -) without aperture phase error

(——) with quadratic phase error

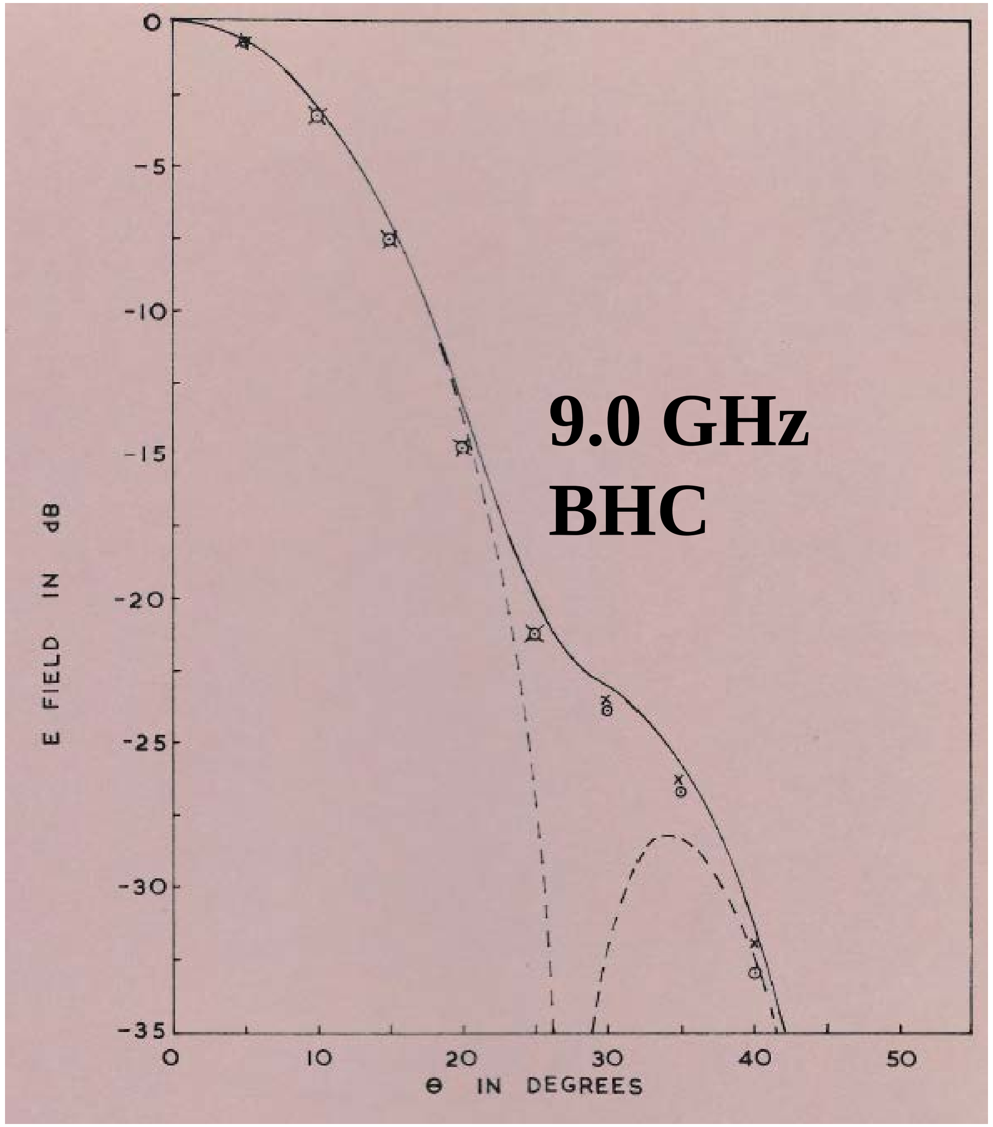
Experimental Data:

⊙ E-plane

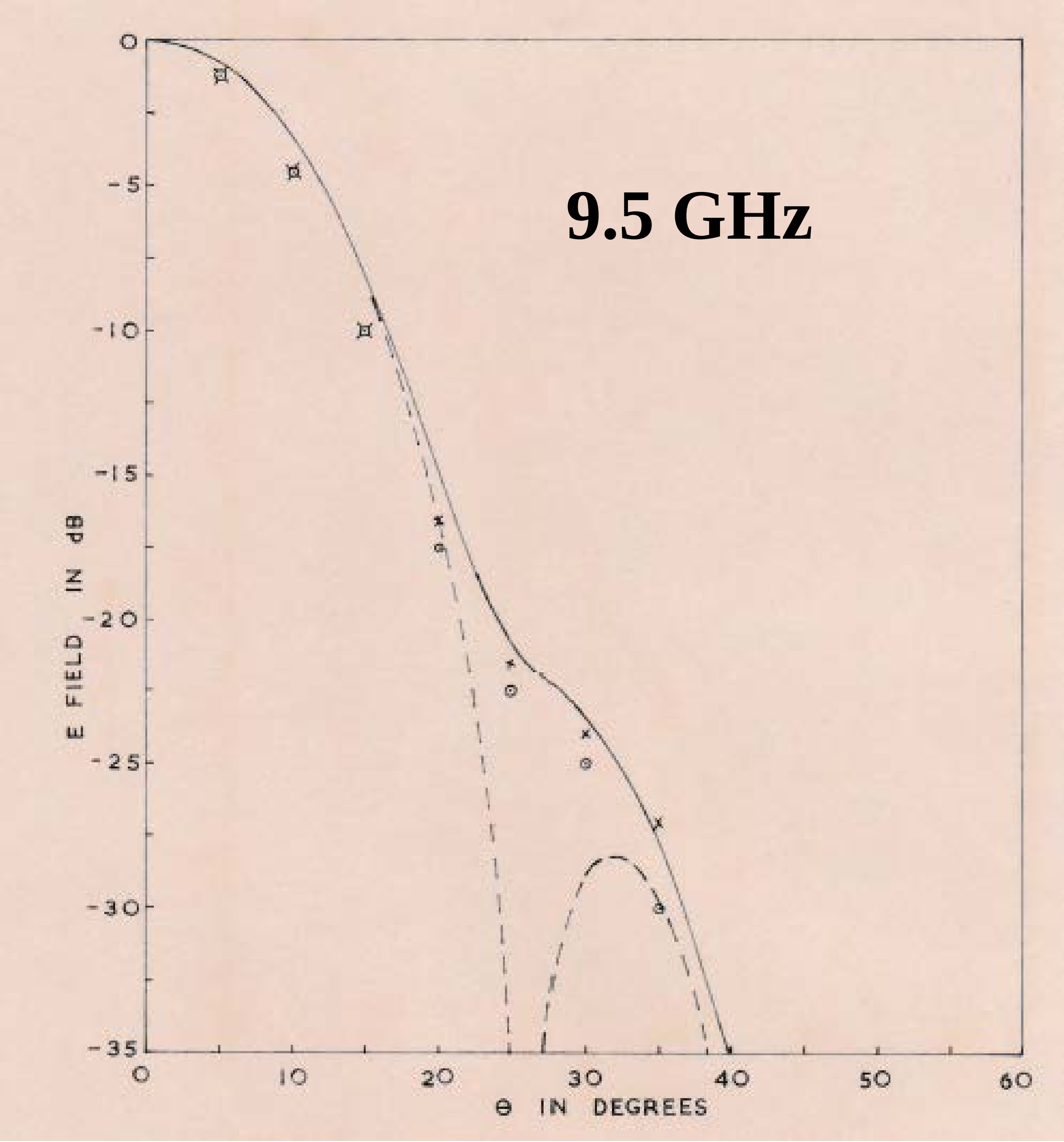
× H-plane

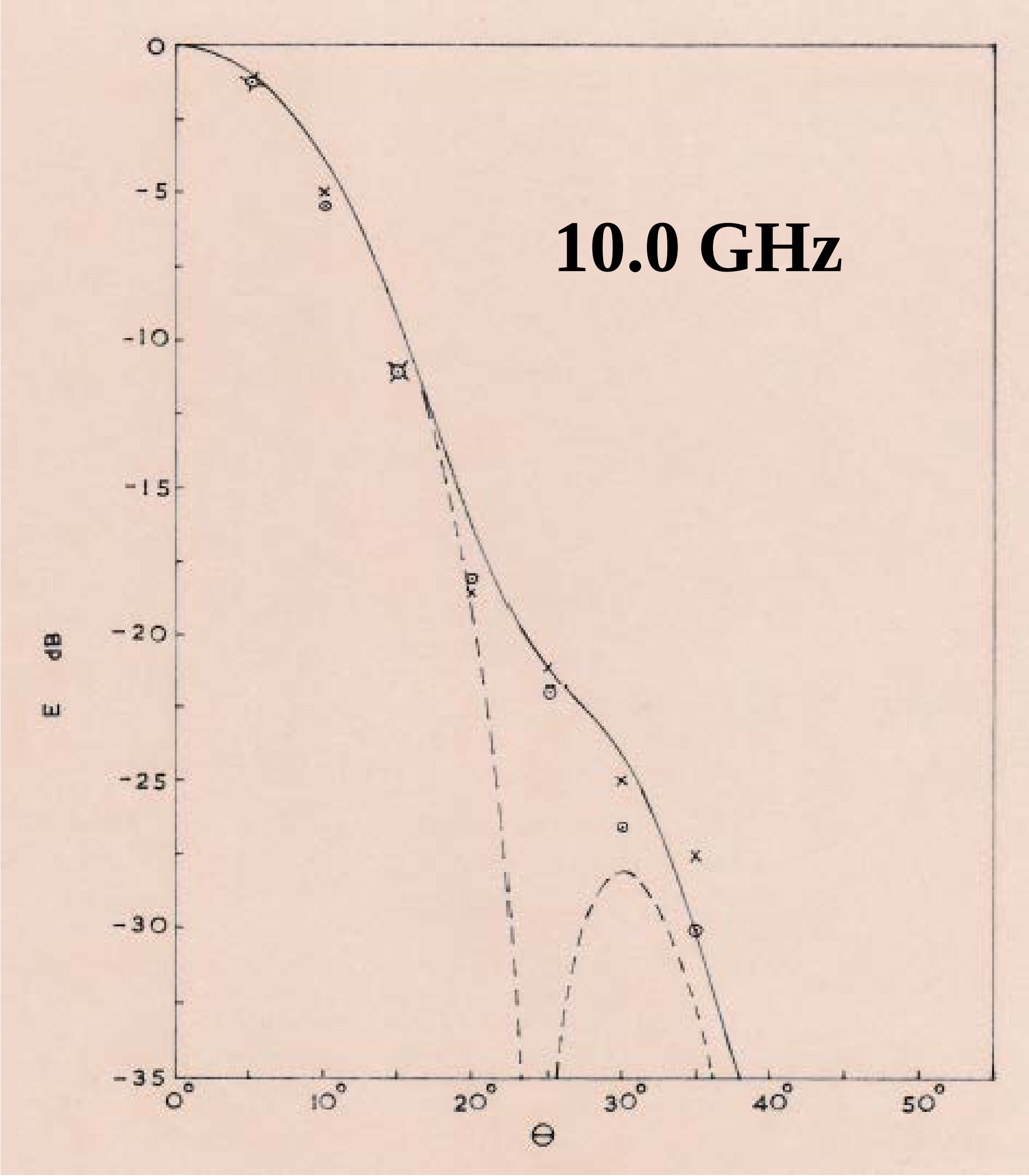


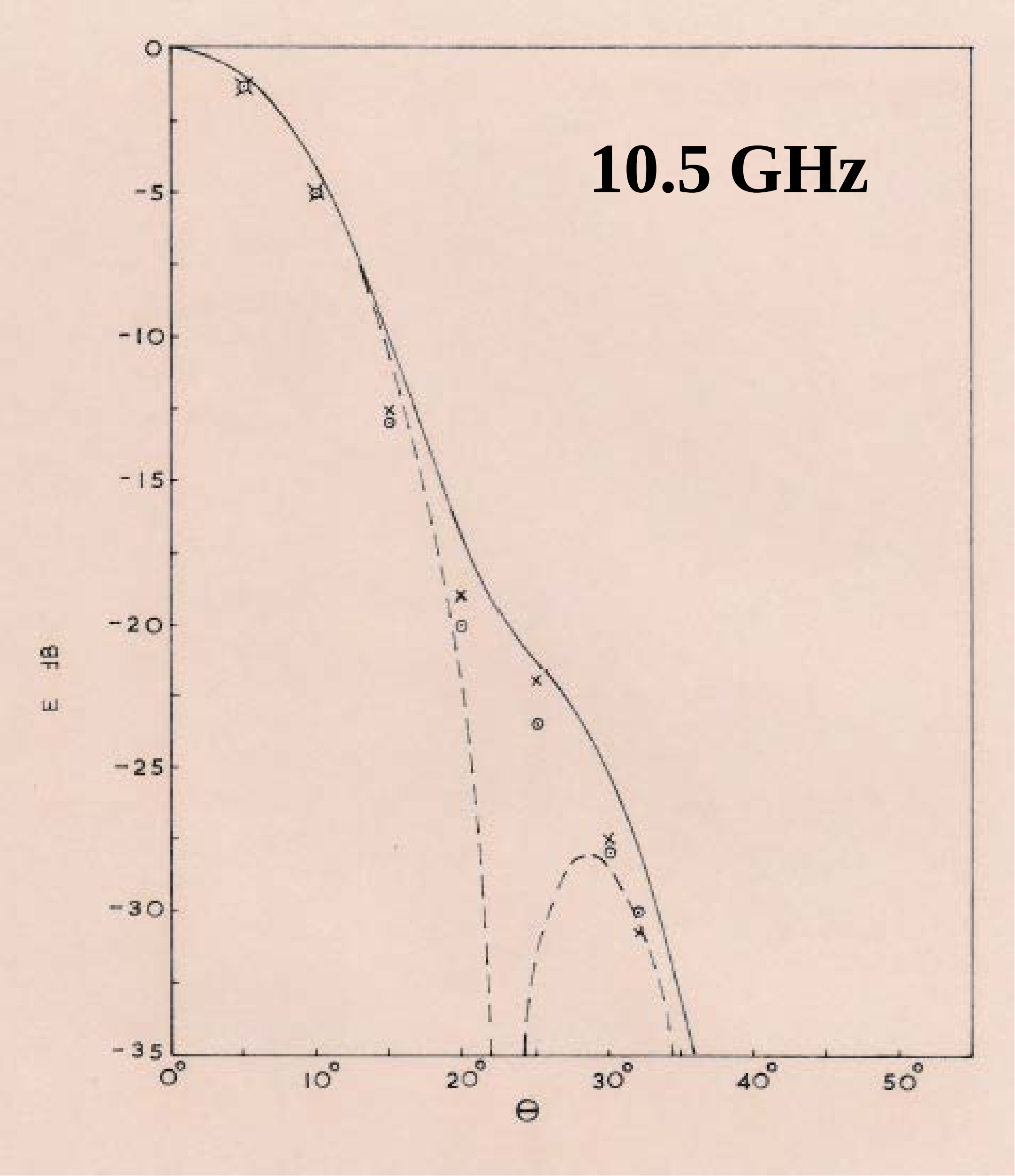
8.5 GHz



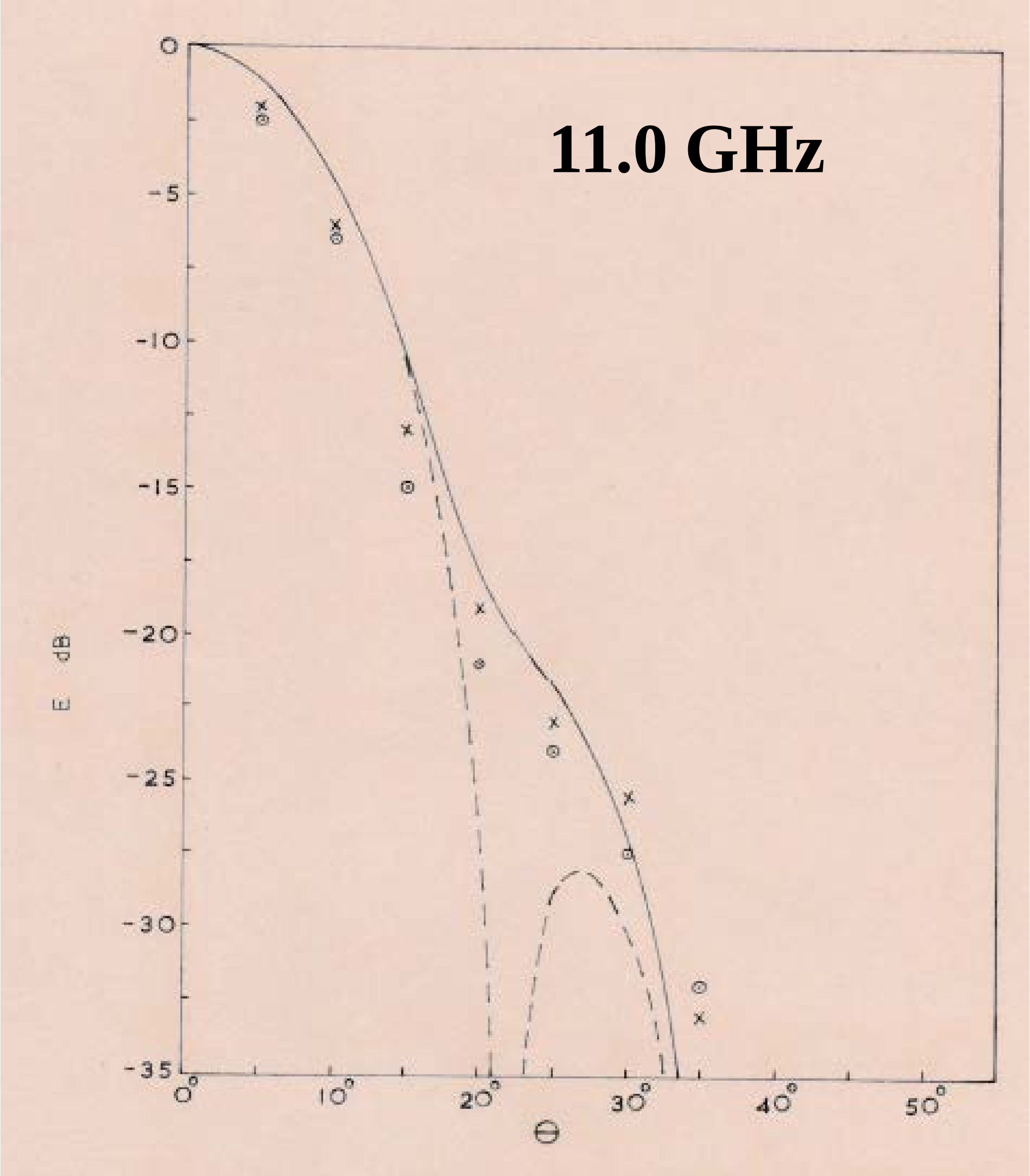
9.0 GHz
BHC


9.5 GHz
E FIELD IN dB
0
-5
-10
-15
-20
-25
-30
-35
0
10
20
30
40
50
60
θ IN DEGREES

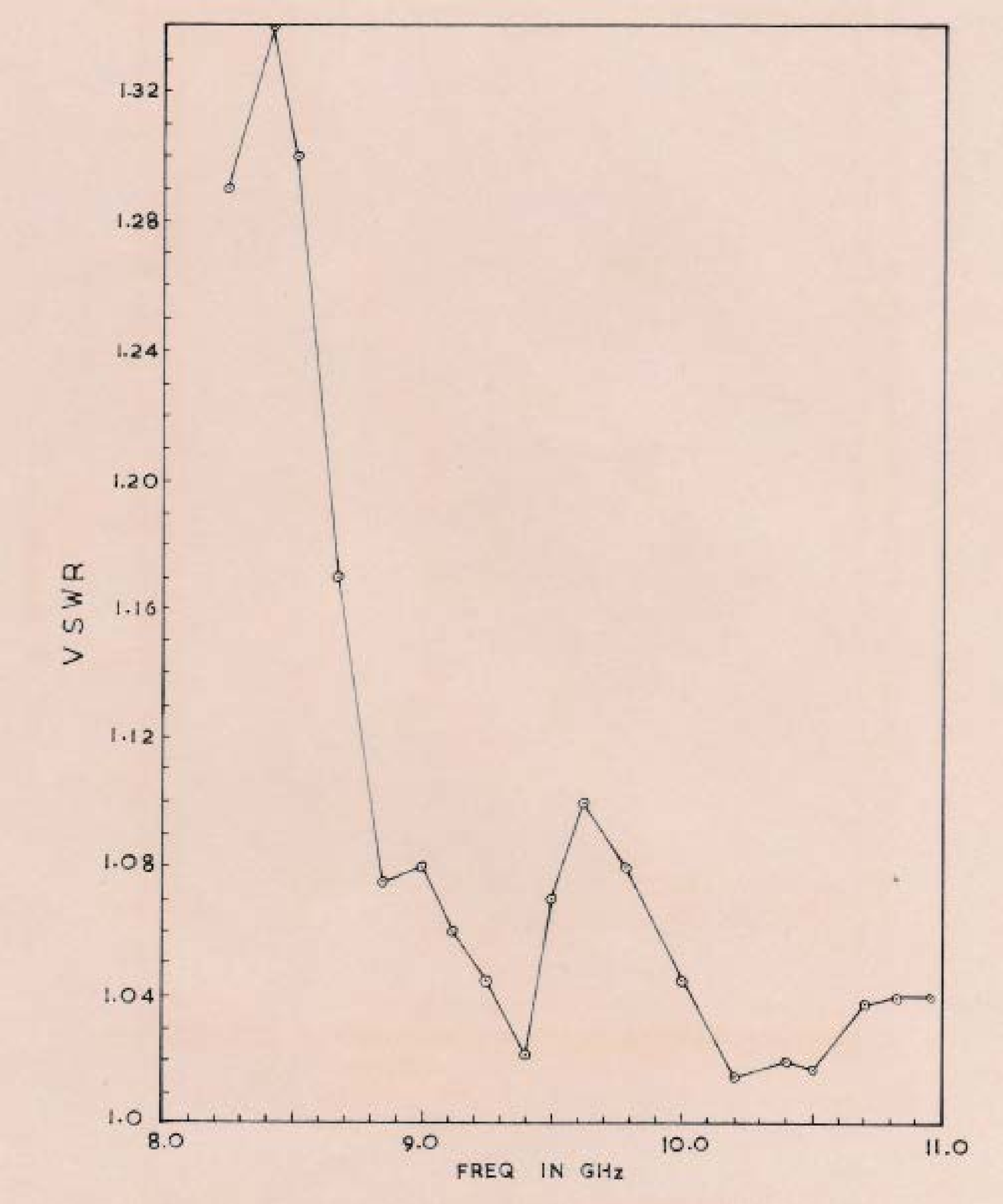

10.0 GHz
E dB
0
-5
-10
-15
-20
-25
-30
-35
0°
10°
20°
30°
40°
50°
Θ



10.5 GHz



11.0 GHz



Measured Input VSWR at the throat of the Experimental Narrow Flare Horn of 12º Half Flare Angle as Function of Frequency

Third Phase: Study of Propagation and Radiation Characteristics of Wide-flare Corrugated Conical Horn

- **Derivation of Spherical Hybrid Modes in the Horn and Aperture Field**
- **Far-field pattern by Vector Diffraction**
- **Radiation Field by Spherical Wave Expansion**
- **Computation of Phase-Centre Location in E and H planes**
- **Analysis of Lens-corrected Scalar Feeds**
- **Performance of Parabolic Reflector with Scalar Feed**
- **An Experimental 30^o Half-Flare Corrugated Conical Horn**
- **Experimental Results: Patterns and Input VSWR**
- **Analysis of Modified Scalar Horn with Corrugations only near Aperture**

Highlights of Third Phase Results (1)

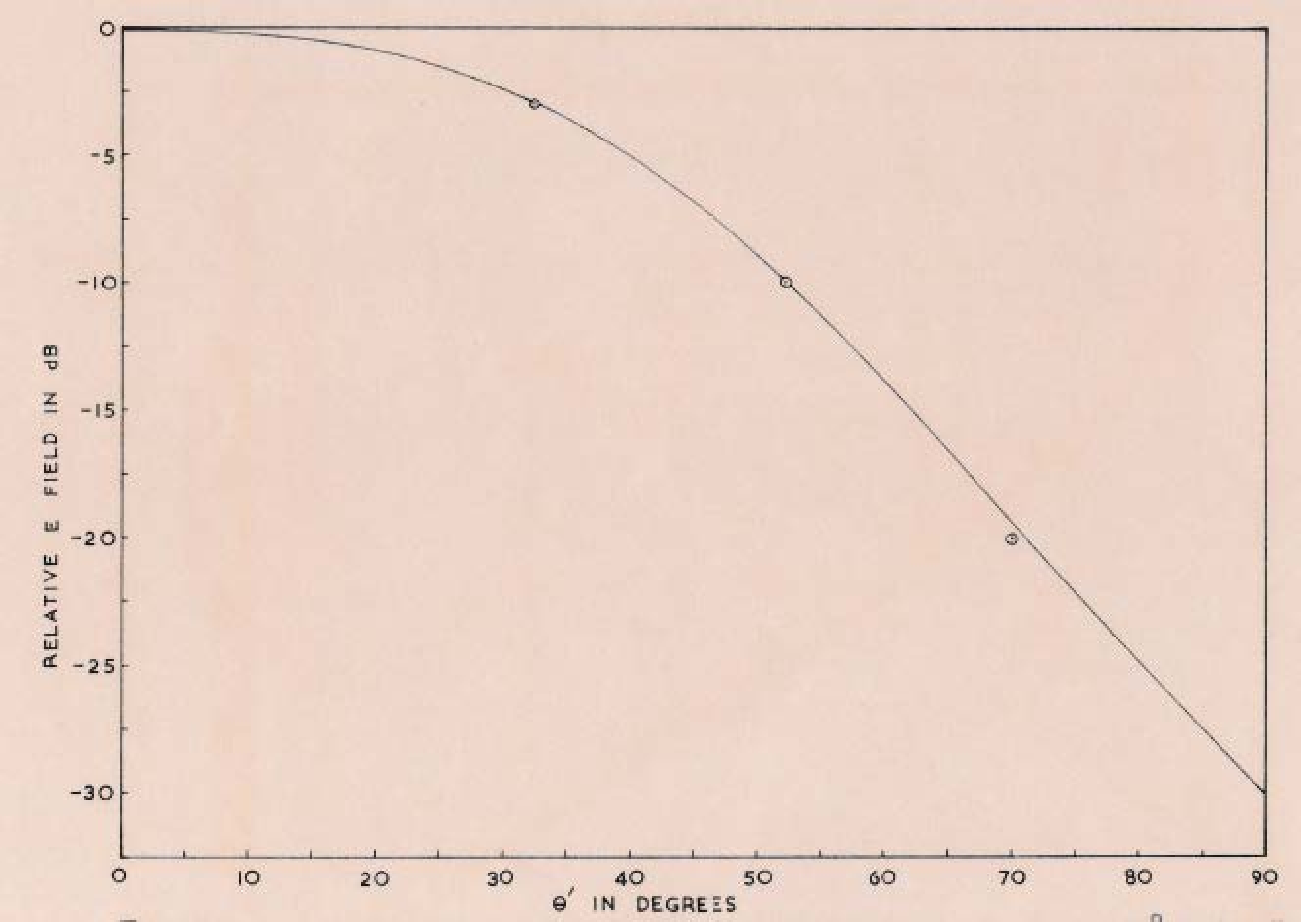
- The concept of quadratic phase error could not be utilized for computing hybrid mode radiation patterns of wide-flare corrugated horn as $\Delta > \lambda/2$. These were derived from vector diffraction theory by Kirchhoff-Huygen integration over the spherical wavefront at the aperture. The aperture field was available from Clarricoats' analysis of spherical hybrid modes in scalar horn.
- The computed HE_{11} radiation pattern matched the experimental pattern of Kay's scalar horn extremely well subject to the usual error of reading from a graph.
- HE_{11} radiation patterns were also computed using modal expansion method in which the aperture field is expanded in terms of spherical wave functions.
- The far-field patterns obtained by the two methods agreed very well for various flare angles and horn lengths.

Highlights of Third Phase Results (2)

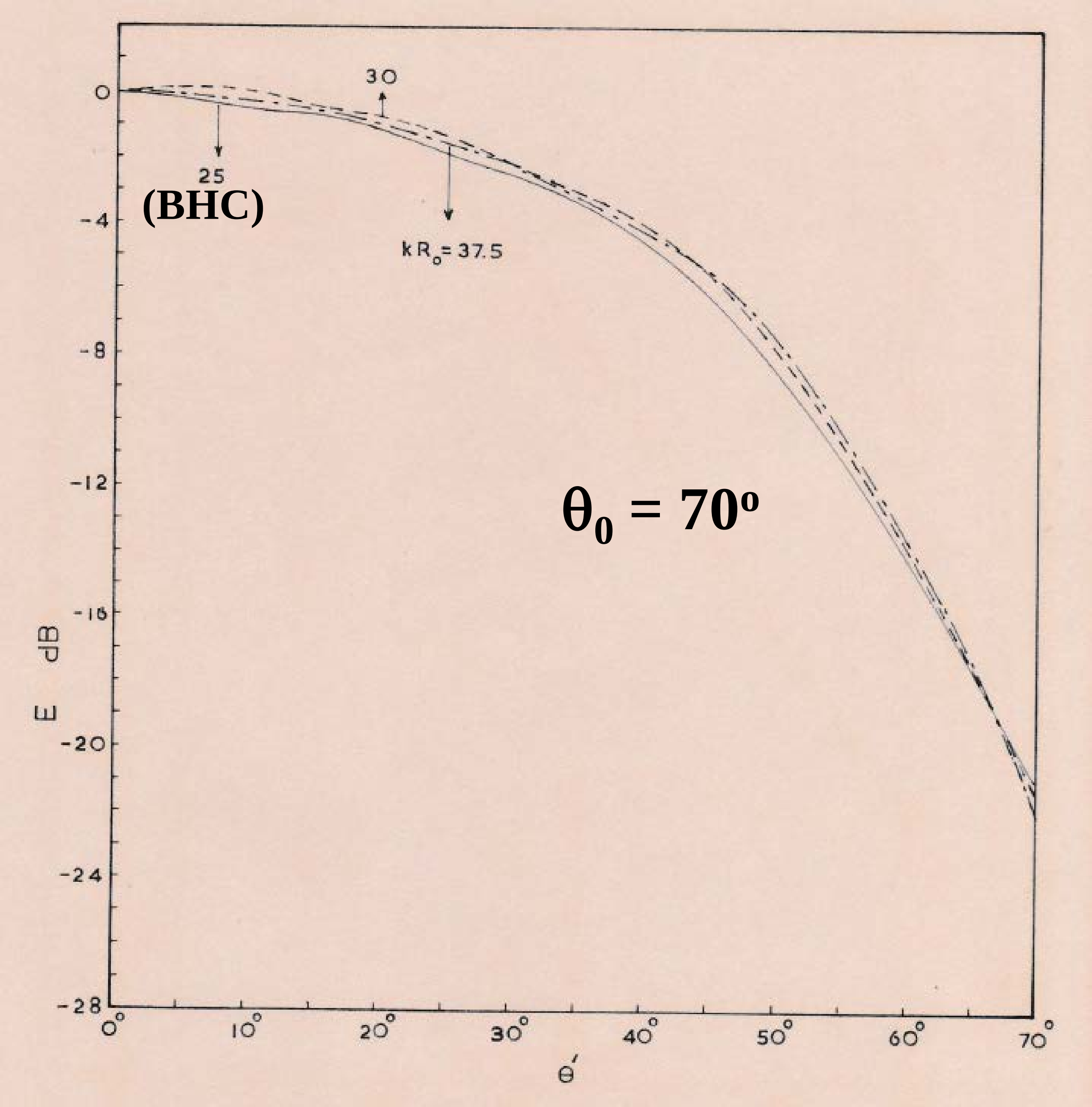
- The locations of the principal plane phase centres were computed theoretically to confirm that they are nearly coincident.
- Patterns of lens-corrected scalar horns were computed with plano-convex and meniscus lens at the aperture. Effects of lens on the aperture distribution, beamwidth and sidelobe level were thoroughly examined.
- Performance characteristics of front-fed parabolic reflector with wide-flare scalar horn at focus were also computed.

Highlights of Third Phase Results (3): Experiments

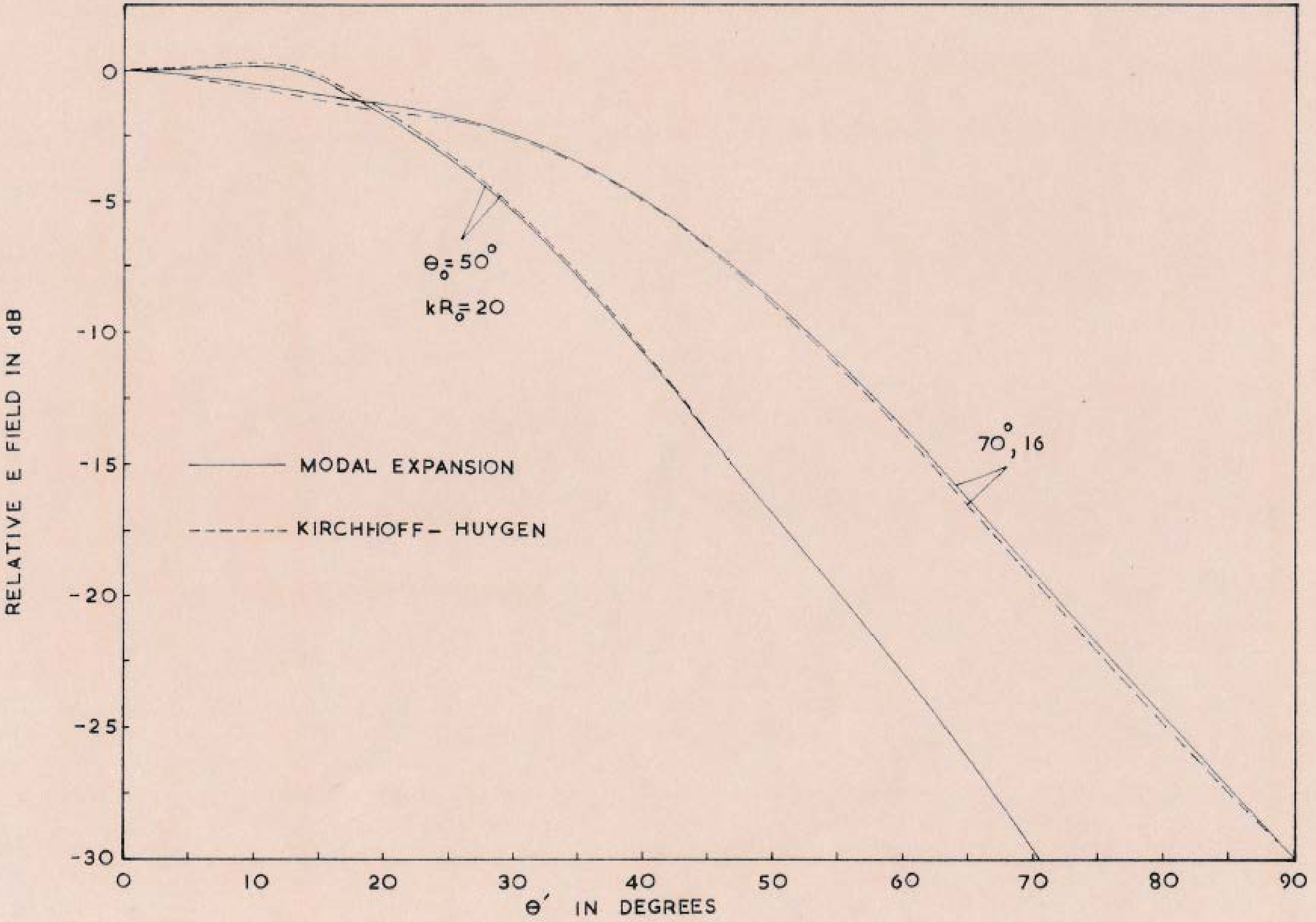
- A 30^{o} half-flare scalar horn (with corrugations perpendicular to the wall) was fabricated and patterns measured over 8.5-11.0 GHz, which showed very good agreement with the theoretical patterns.
- The maximum value of measured VSWR over this band was about 1.7 indicating good matching condition.



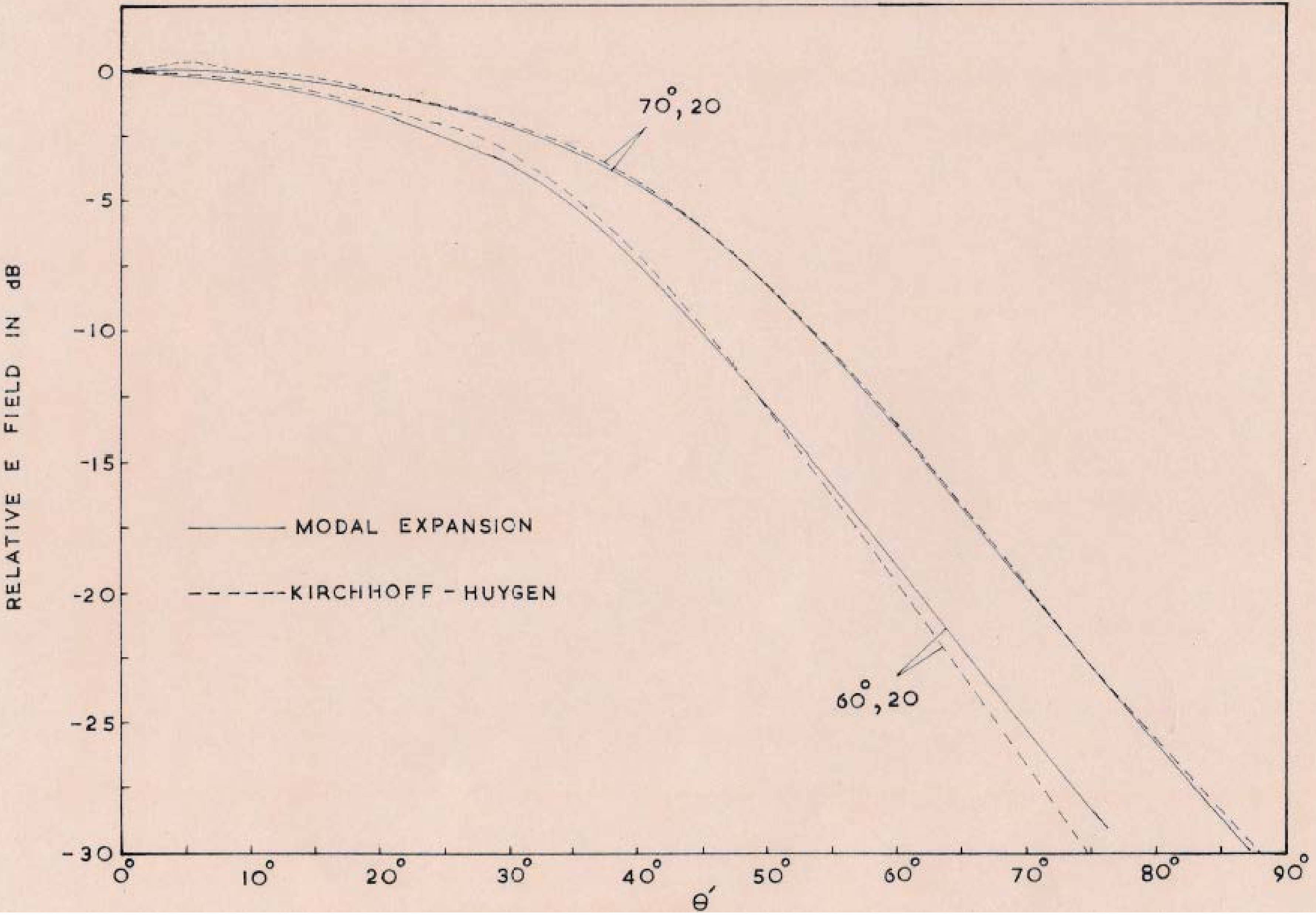
Theoretical Radiation Pattern of Corrugated Horn of 70º Half Flare Angle agrees almost exactly with experimental data of Kay's Scalar Horn



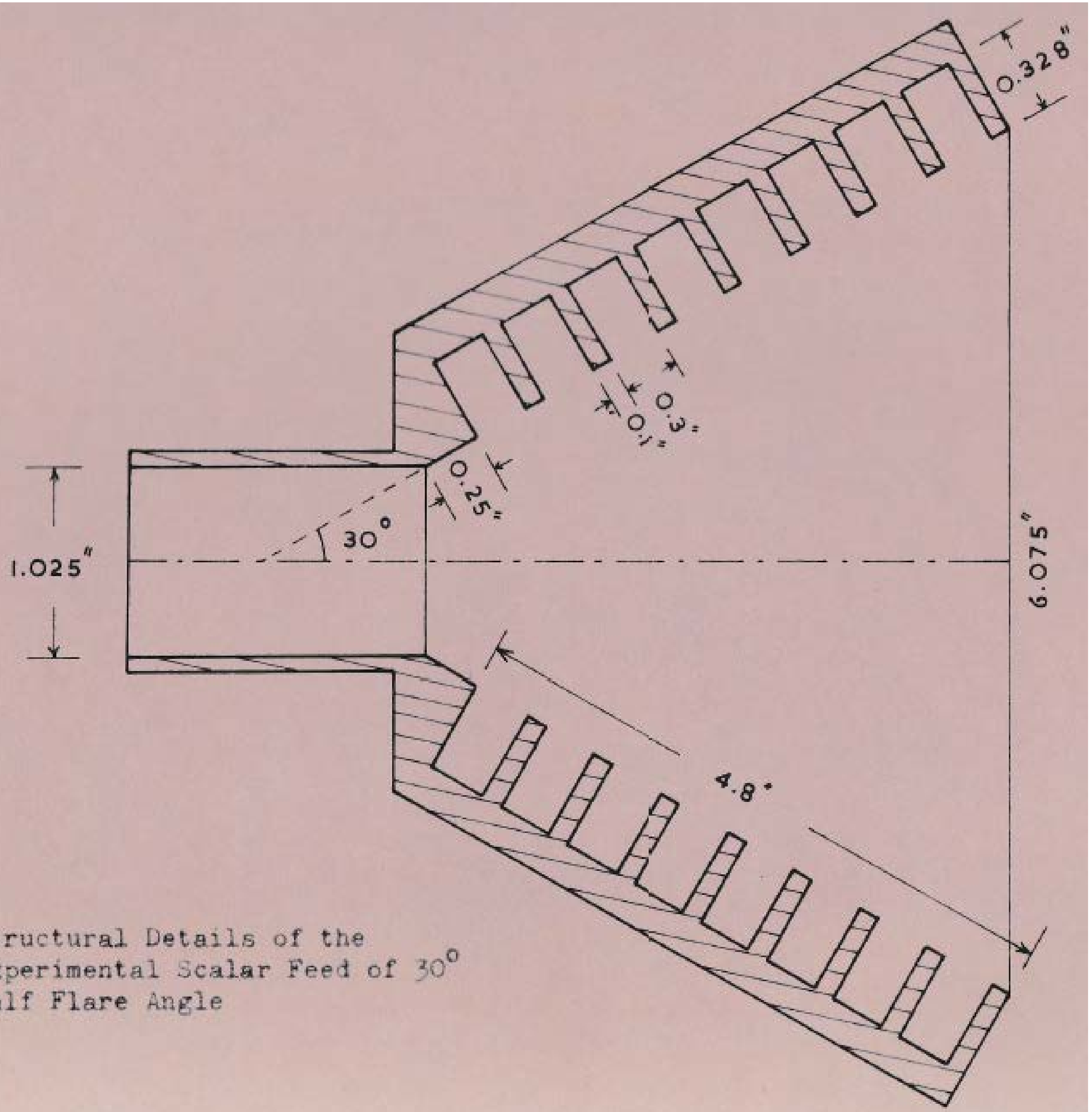
θ_0 = 70° scalar horn patterns for different normalized horn lengths



0
-5
-10
-15
-20
-25
-30
RELATIVE E FIELD IN dB
0
10
20
30
40
50
60
70
80
90
θ' IN DEGREES
$\theta_o = 50^\circ$
$kR_o = 20$
70°, 16
MODAL EXPANSION
KIRCHHOFF- HUYGEN


RELATIVE E FIELD IN dB
0
-5
-10
-15
-20
-25
-30
0°
10°
20°
30°
40°
50°
60°
70°
80°
90°
θ′
70°, 20
60°, 20
MODAL EXPANSION
KIRCHHOFF - HUYGEN

Structural Details of the Experimental Scalar Feed of 30º Half Flare Angle


0.328"
0.3"
0.1"
0.25"
30°
1.025"
6.075"
4.8"

Structural Details of the
Experimental Scalar Feed of 30°
Half Flare Angle

Theoretical and Measured Patterns of Experimental 30º Half Flare Scalar Horn

8.5 – 11.0 GHz

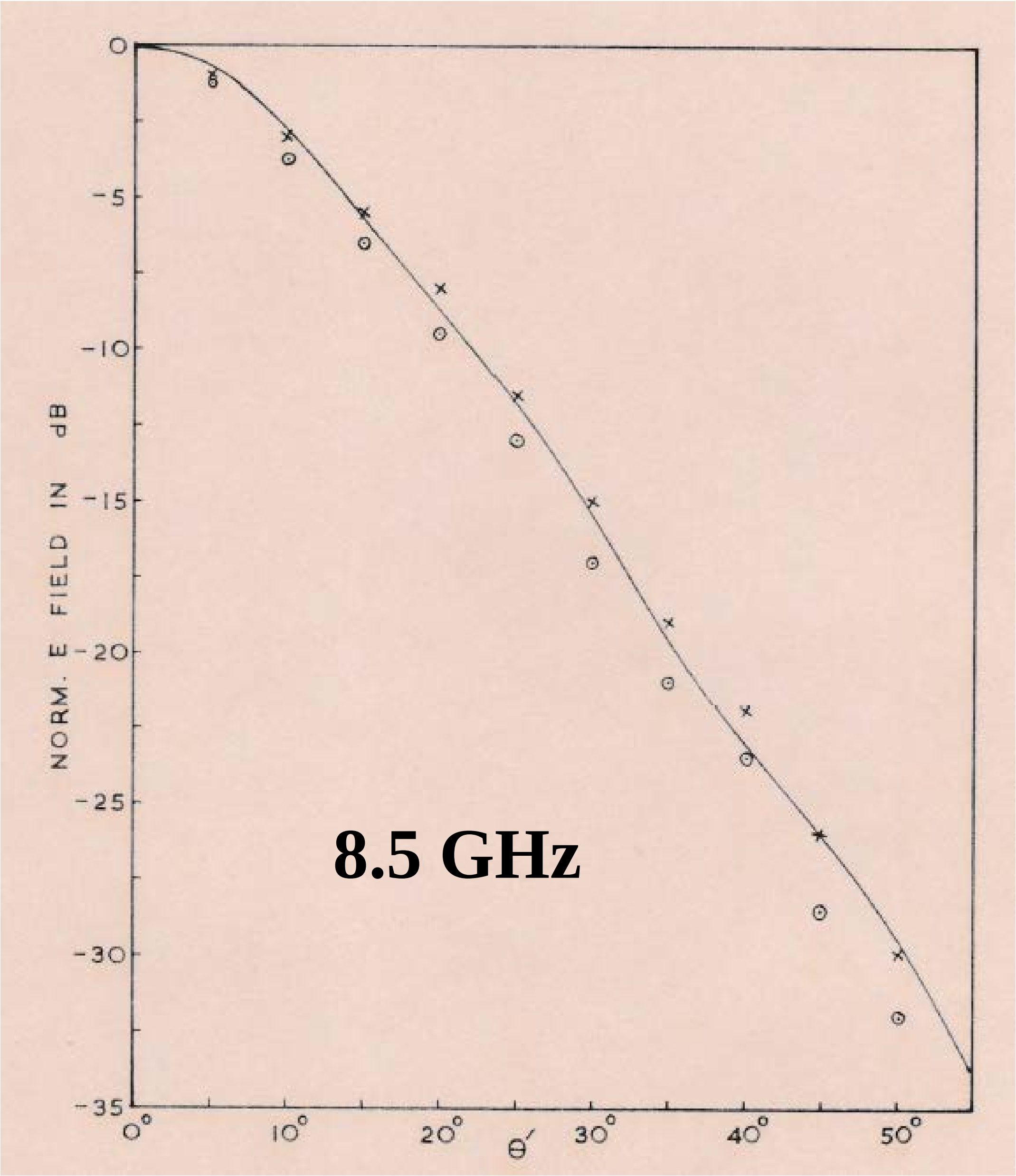
Computed Pattern:

(——) spherical phase-front at aperture

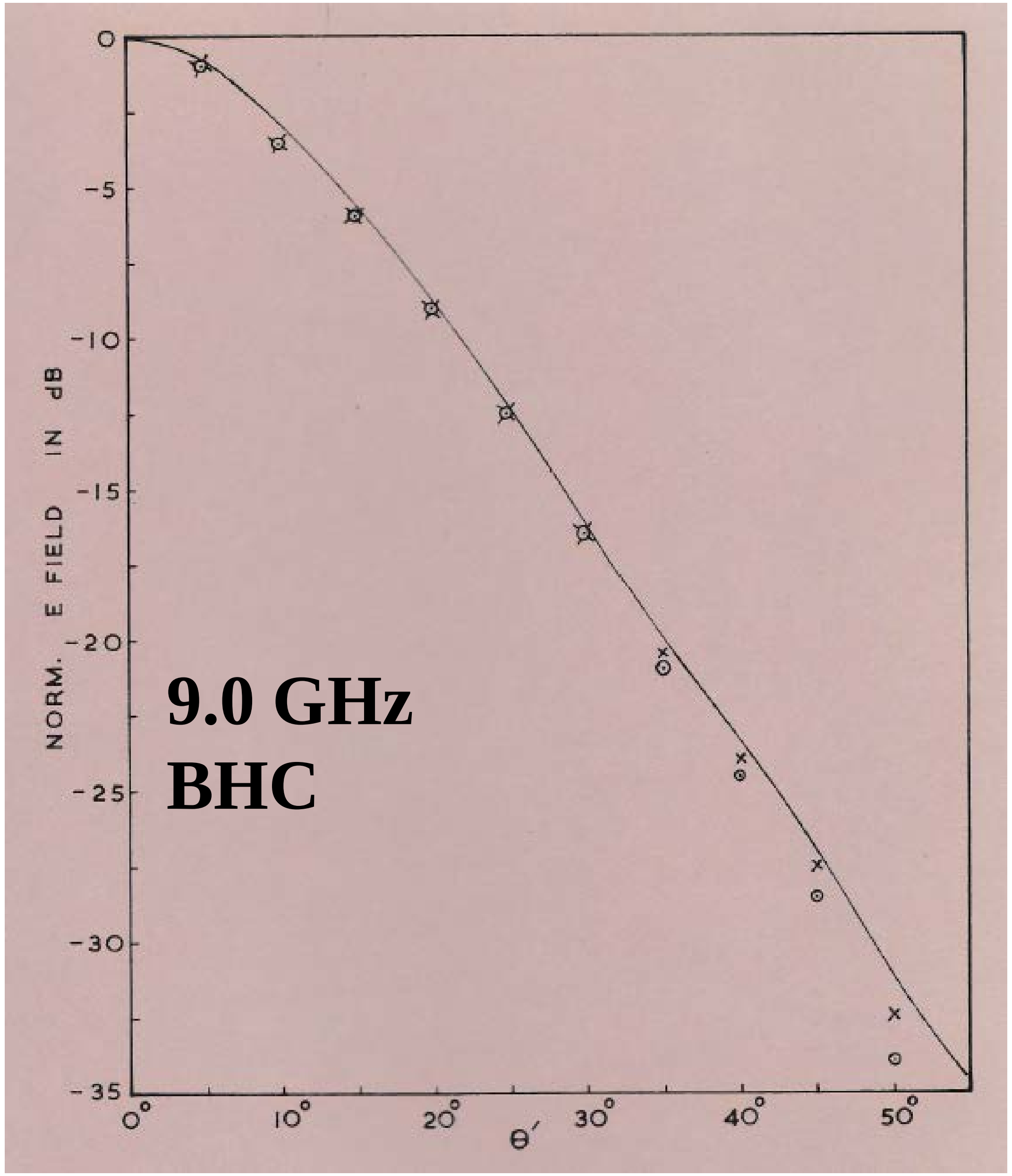
Experimental Data:

⊙ E-plane

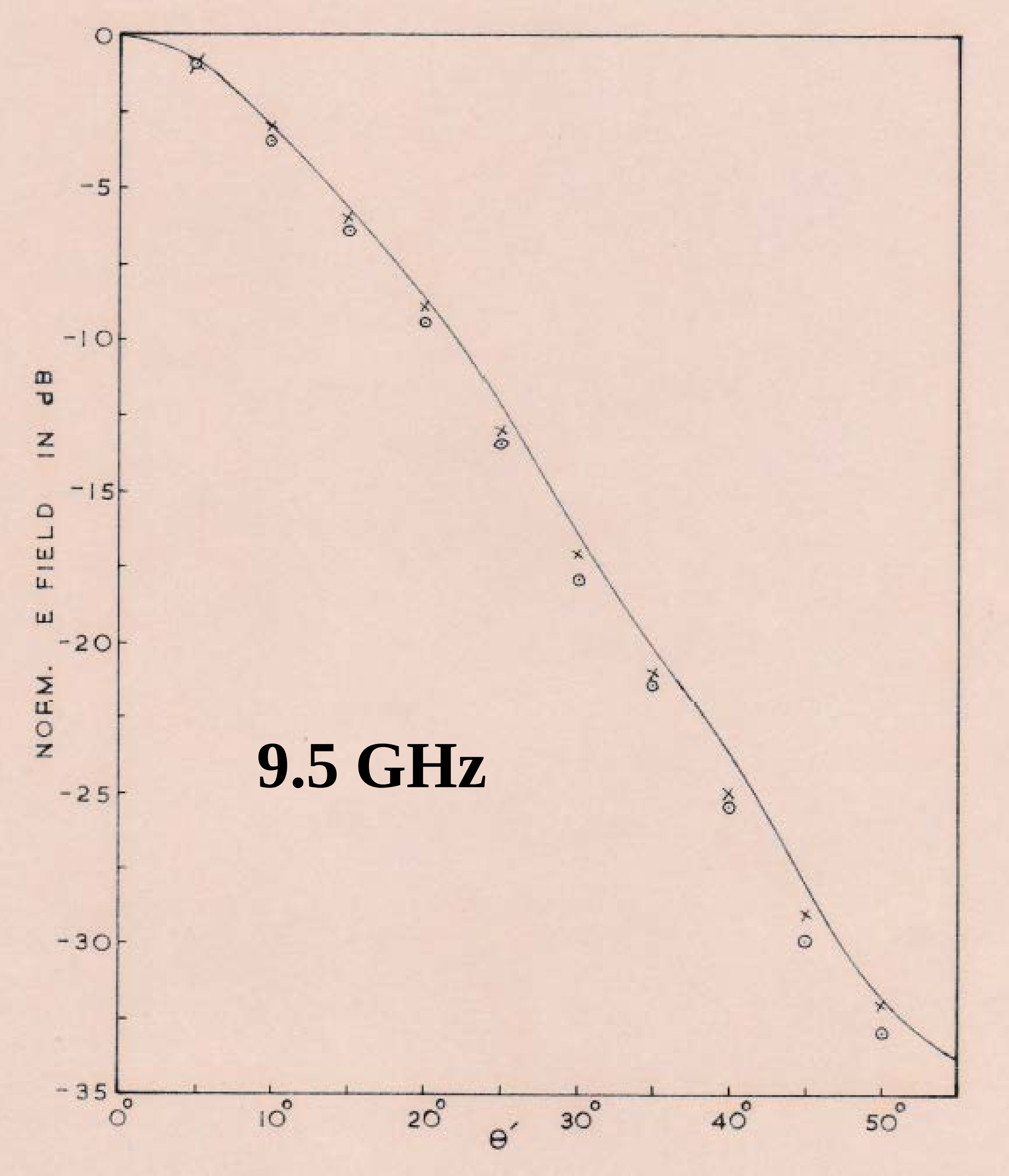
× H-plane



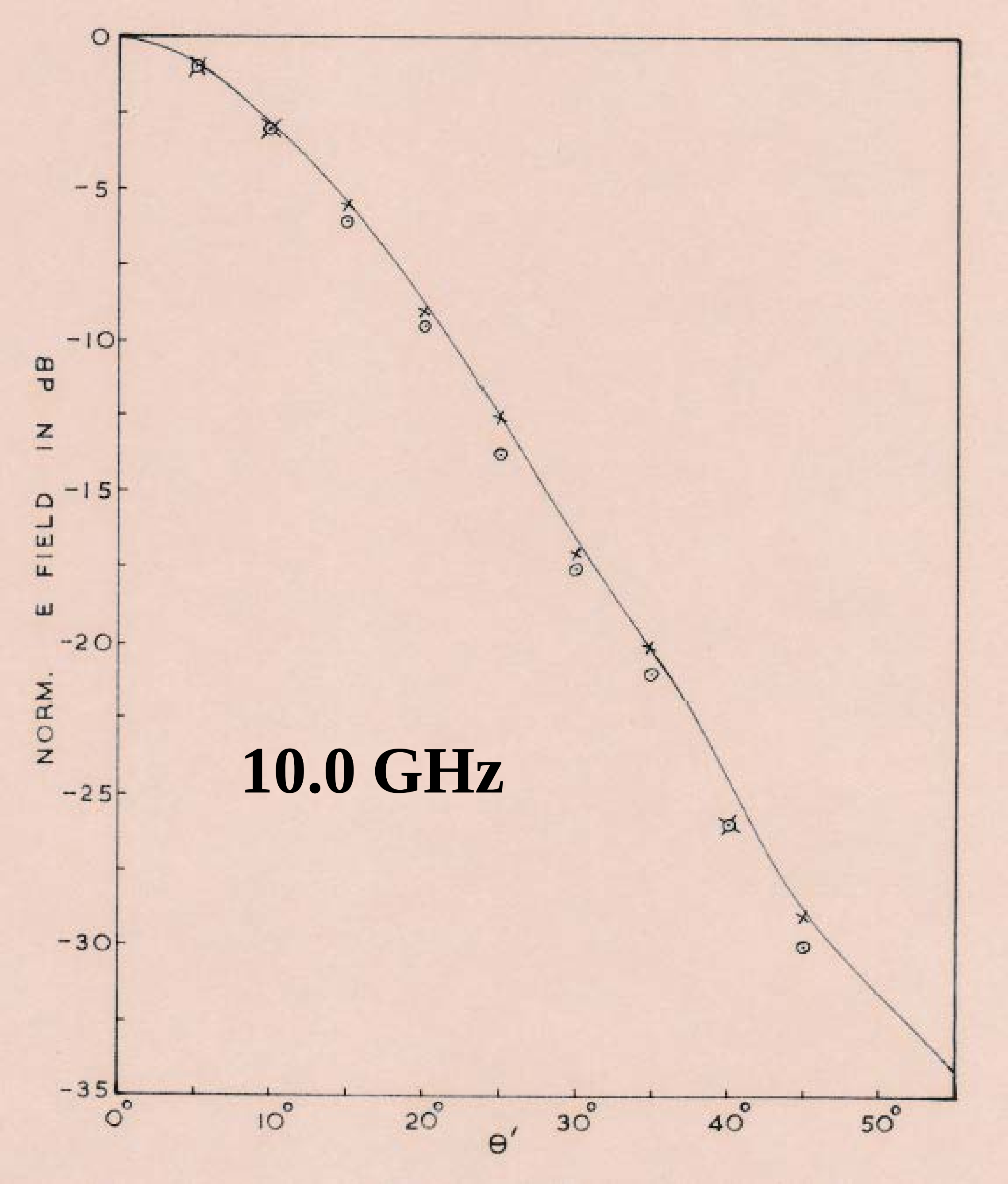
8.5 GHz



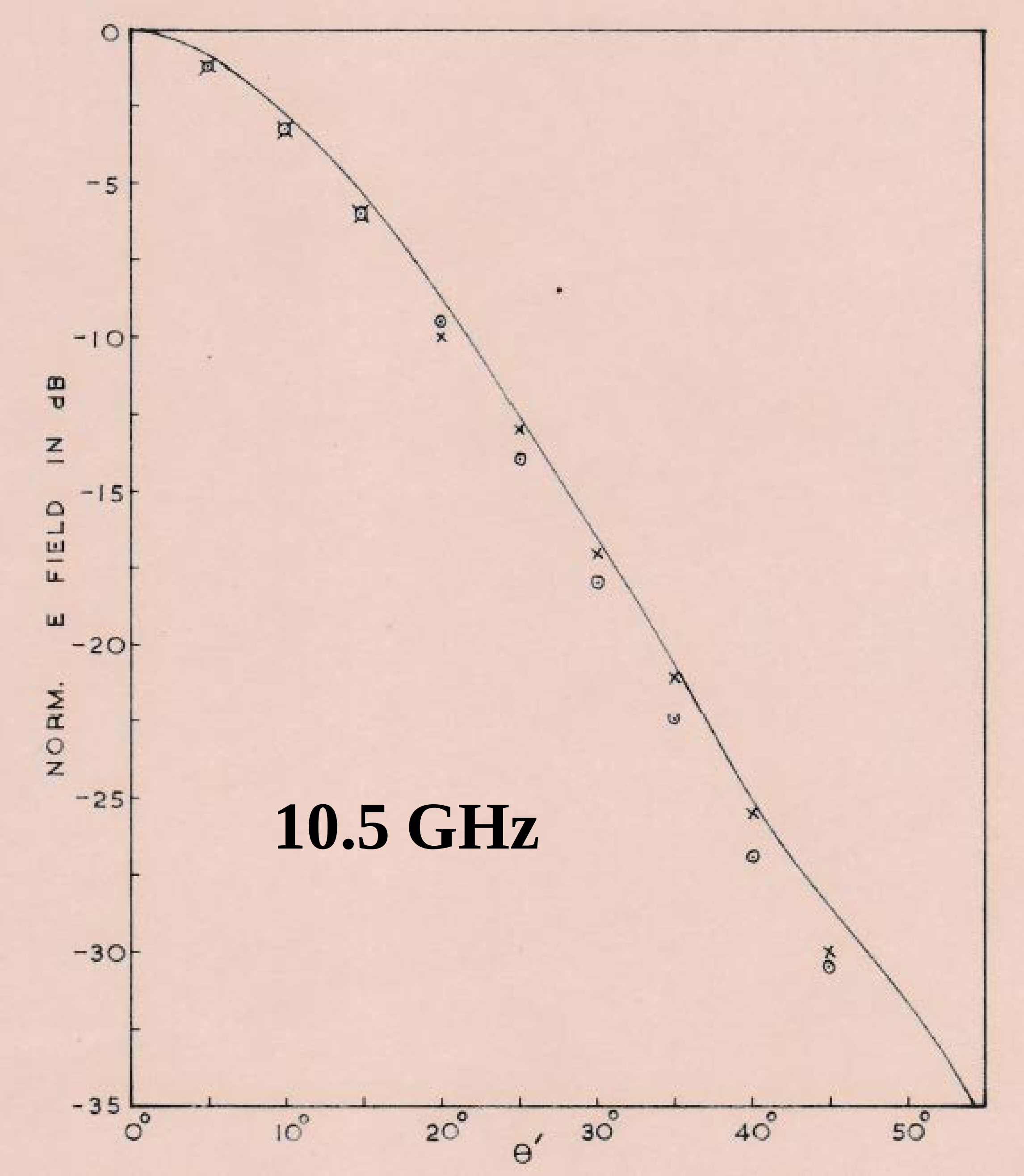
9.0 GHz
BHC



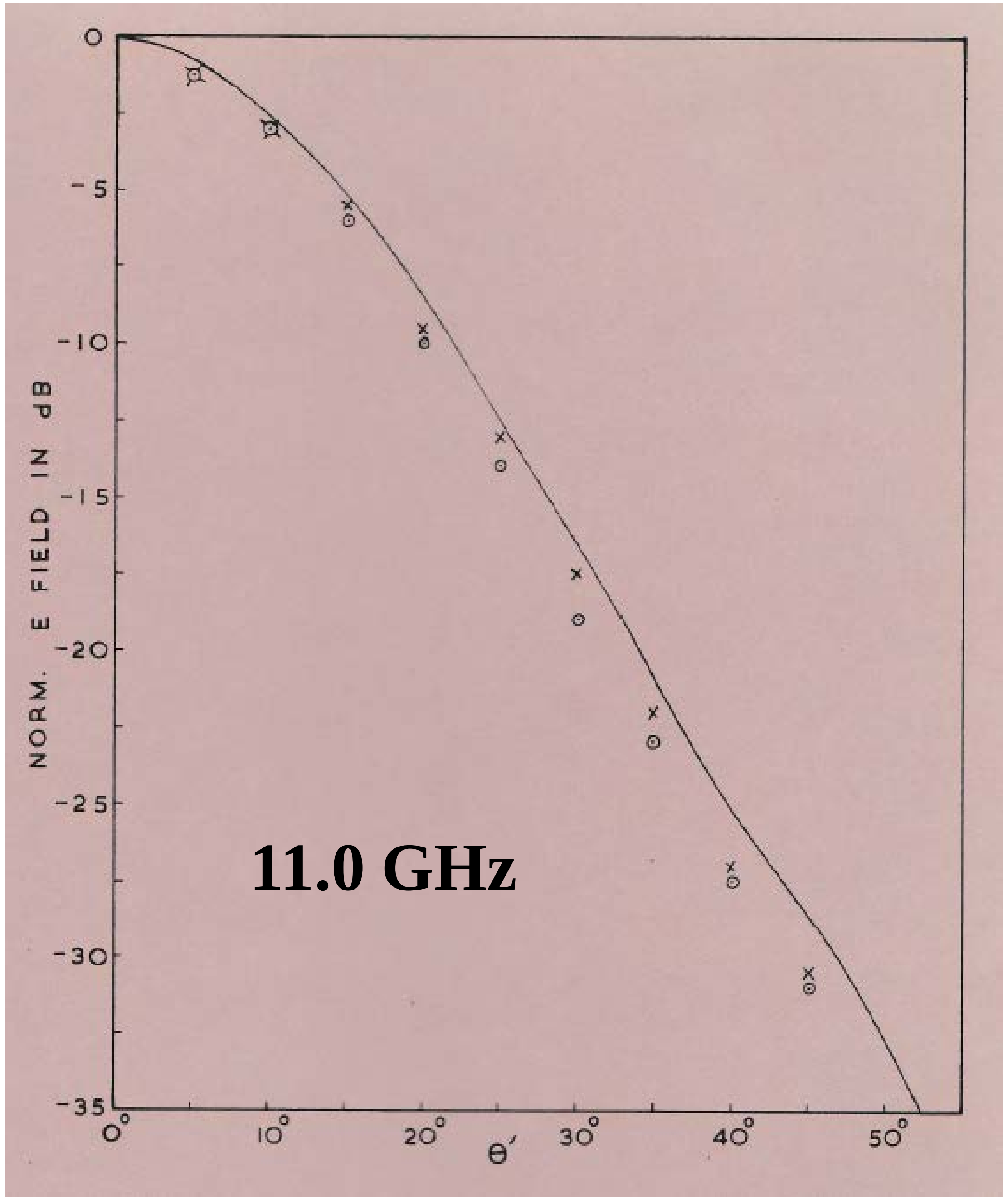
9.5 GHz



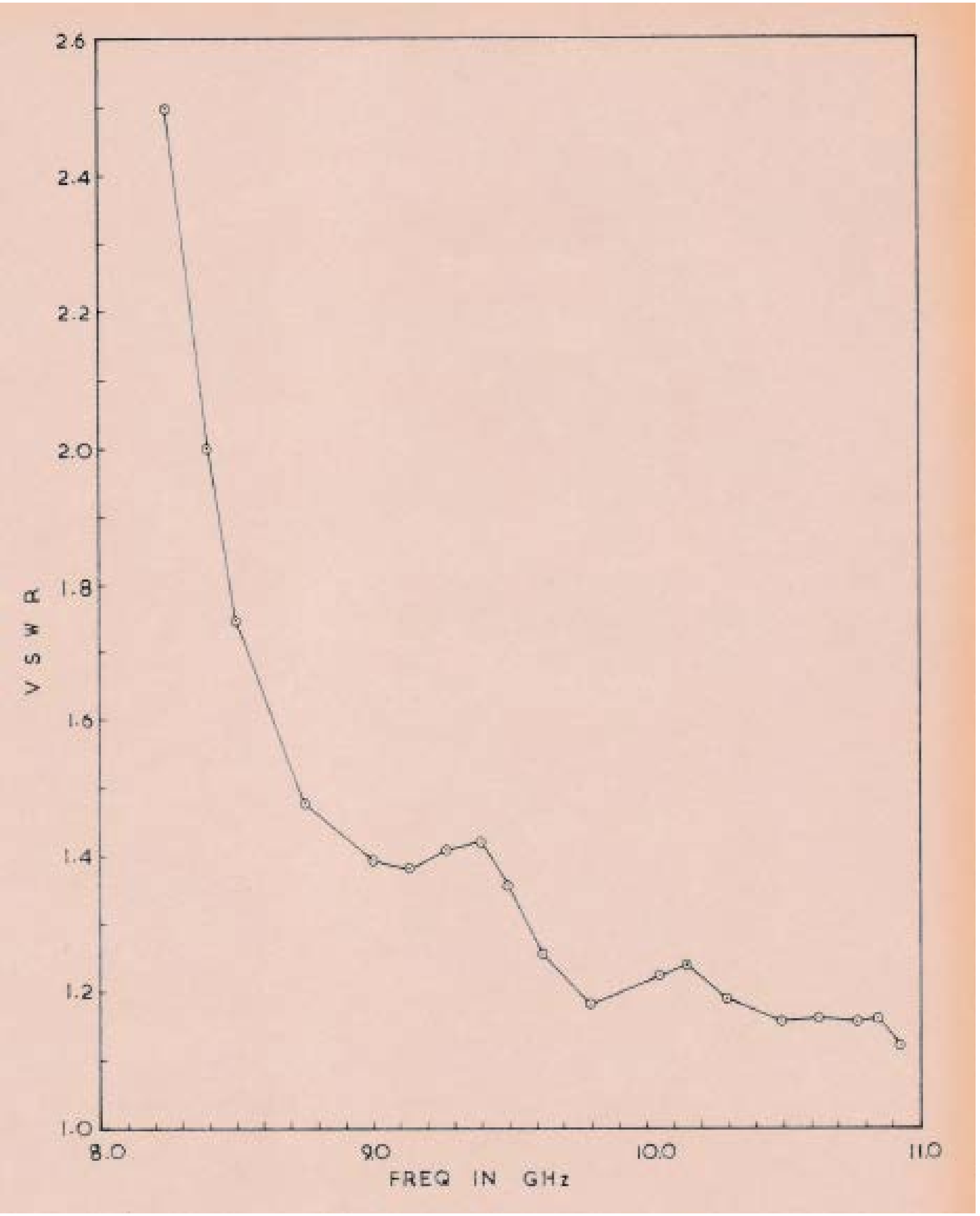
10.0 GHz



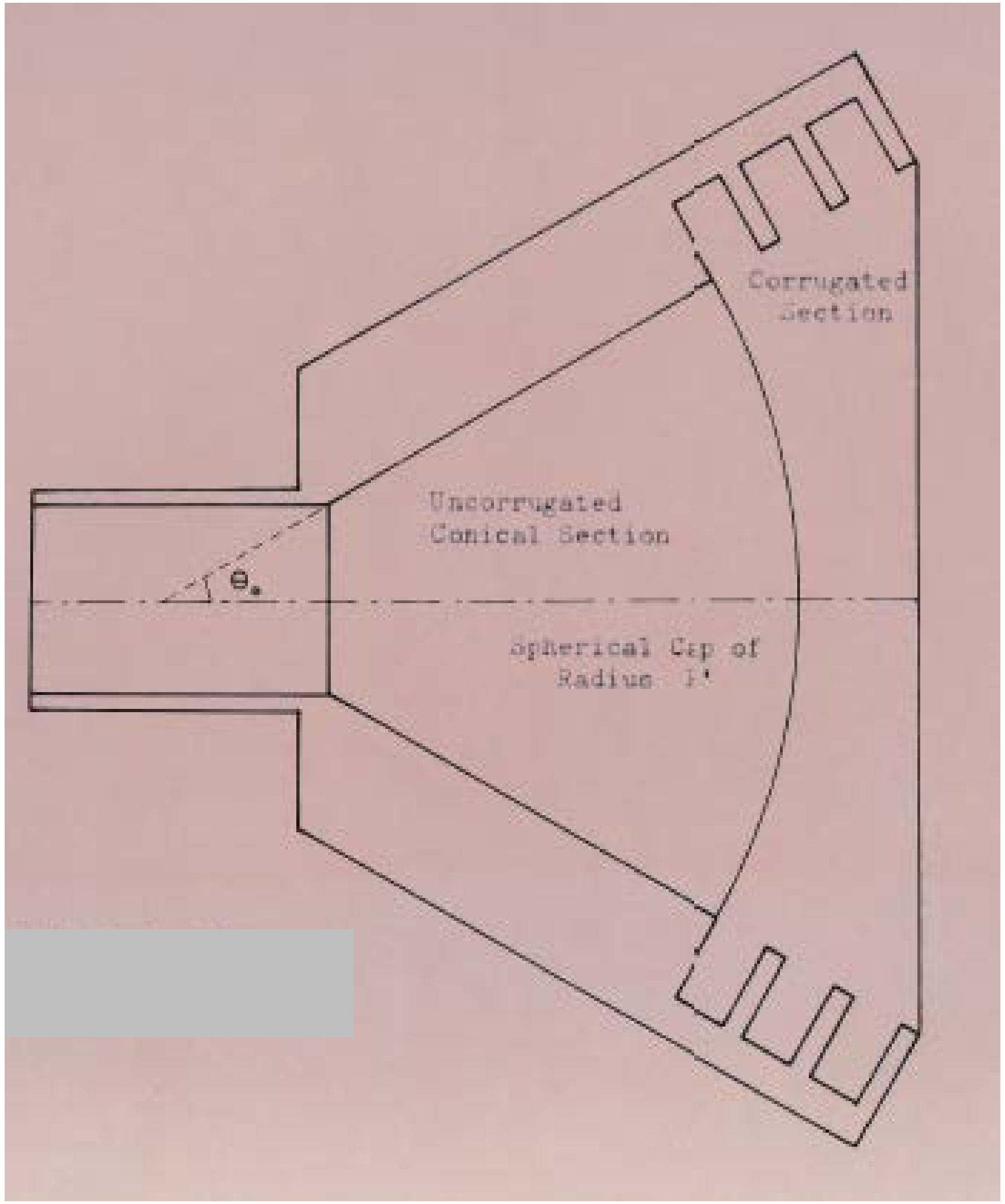
10.5 GHz



11.0 GHz



Measured Input VSWR at the throat of the Experimental Wide Flare Horn of 30^o Half Flare Angle as Function of Frequency


Corrugated Section
Uncorrugated Conical Section
θ_0
Spherical Cap of Radius R'

Modified Wide-Flare Corrugated Conical Horn with Corrugations only near the Aperture

Highlights of Third Phase Results (4) (Modified Scalar Horn)

- With TE_{11} mode incident from the un-corrugated section, equations developed from mode-matching over the spherical cap at the junction between two sections were solved with 6 modes each in corrugated and un-corrugated sections for different flare angles.
- The reflection coefficient of the incident TE_{11} mode and excitation of higher order modes in un-corrugated section were found to be negligible.
- Power launched in the HE_{11} and the first five higher order hybrid modes in corrugated section was computed. The computed results showed that depending on the flare angle, at least 80% power is excited into the dominant HE_{11} mode. (For flare angles of 60^o and 140^o, the fraction is approximately 84% and 81%, respectively).
- The fraction of the incident power transferred to the modes in the corrugated section decreases sharply for the higher order modes and is less than 1% for the 6th mode.

Excitation of Modified Conical Scalar Horn
Computed P_m/P_{in} for first six modes in corrugated section

m	P_m/P_{in} in per cent				
	$\theta_o = 30^o$	$\theta_o = 40^o$	$\theta_o = 50^o$	$\theta_o = 60^o$	$\theta_o = 70^o$
1	83.87	83.36	82.67	81.79	80.67
2	4.39	4.56	4.80	5.11	5.53
3	3.59	3.69	3.81	3.96	4.13
4	1.36	1.40	1.46	1.54	1.64
5	1.27	1.31	1.35	1.41	1.49
6	0.68	0.70	0.73	0.76	0.81

Concluding Remarks

Looking back after about 50 years, the research carried out during those years in Queen Mary College generates a fresh sense of satisfaction. Quite a few aspects of corrugated waveguides and horns were explored from which many interesting characteristics had emerged. Being a time-bound doctoral research, perhaps all the explorations could not reach great depth but did certainly open up scopes of further fruitful research. Experts will judge whether this piece of work can earn a place in the history of microwave antenna.

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